What would the CA grid be like at 60% renewables ?
- and how do we make it work?

David E. Culler,
Jay Taneja, Randy Katz
University of California, Berkeley

EETD Lunch Seminar
April 10, 2012

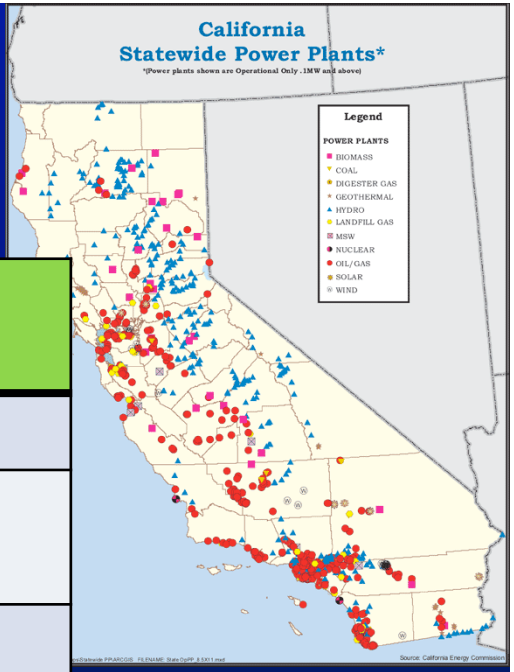
i4 energy

A60

The Renewables Chasm

- Many analytical studies on RPS targets, etc.
  - CA Mandate 2010 → 20%, 2020 → 33%
  - Pathways to 2050 goals
- Many mechanisms for improving the grid
  - DC, DR, markets, supply-following, storage, …
  - Each incremental change runs into severe constraints
- Goal: Step back and understand in broad terms what the challenges "will be" in a sustainable grid
- Understand dynamics at deep penetration
  - How do the roles of existing grid resources change?
  - How does *demand shifting* affect dynamics?
  - How do the critical challenges change?

CA grid today - Supplies



Source	Rated (GW)	Capacity Factor[1]	Total Energy (TWh)	% of Total Energy
Geothermal	2.600	38.7%	8.68	3.8%
Biomass/ Biogas	1.145	43.5%	4.30	1.9%
Small Hydro	1.380	31.7%	3.77	1.7%
Wind	2.812	29.1%	7.06	3.1%
Solar[3]	0.403	28.7%	1.00	0.4%
Nuclear	4.456	85.9%	33.00	14.6%
Hydro	12.574	27.7%	30.05	13.3%
Imports	11.055[2]	66.6%	63.43	28.0%
Thermal	44.339	19.7%	75.43	33.3%
Total	80.764	32.6%	226.71	100.0%

[1] Mean delivered power divided by rated power (excl. import)
[2] For imports, rating is the maximum observed power
[3] Residential net factored into demand

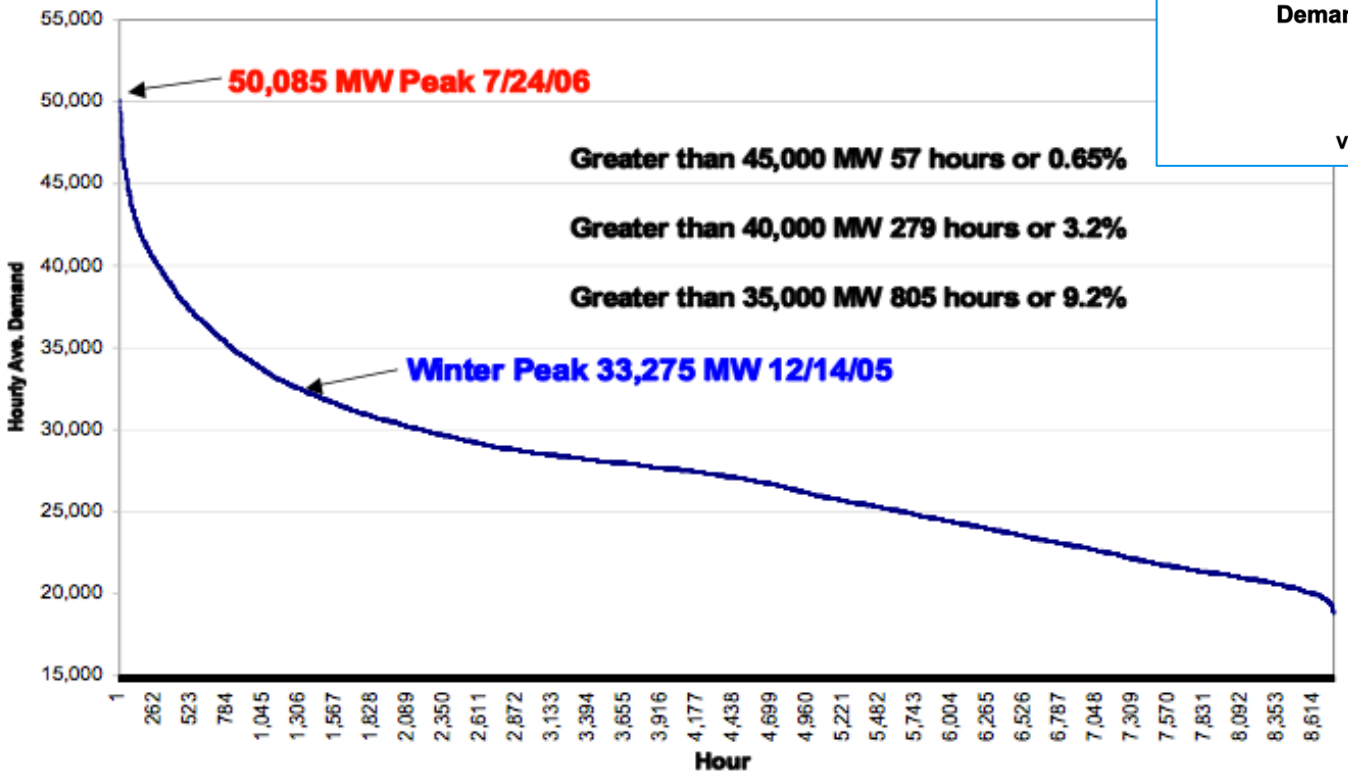
CA grid today – Supply Challenge

California ISO
Your Link to Power

California Independent
System Operator Corporation

CAISO Load Duration Curve

Sept '05 to Sept '06



3

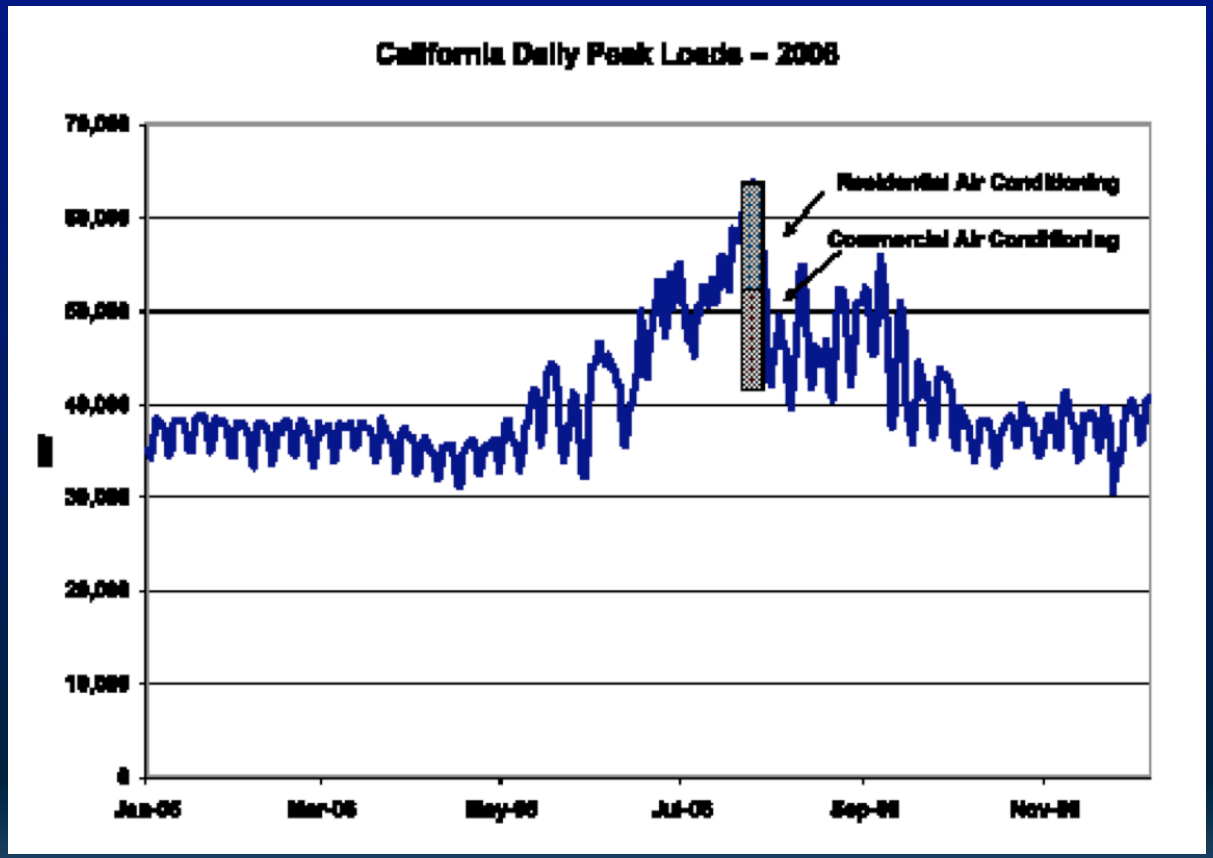
California ISO
Your Link to Power

California Independent
System Operator Corporation

CAISO Operational Needs
from
Demand Response Resources

Jim Detmers
Vice President, Operations

More views – time and blend



POWER CONTENT LABEL

ENERGY RESOURCES	PRODUCT NAME* (projected)	2007 CA POWER MIX** (for comparison)
Eligible Renewable	**55%**	**10%**
-- Biomass & waste	10%	<1%
-- Geothermal	11%	2%
-- Small hydroelectric	13%	6%
-- Solar	10%	<1%
-- Wind	11%	2%
Coal	**16%**	**32%**
Large Hydroelectric	**12%**	**24%**
Natural Gas	**16%**	**31%**
Nuclear	**1%**	**3%**
Other	**<1%**	**0%**
TOTAL	**100%**	**100%**

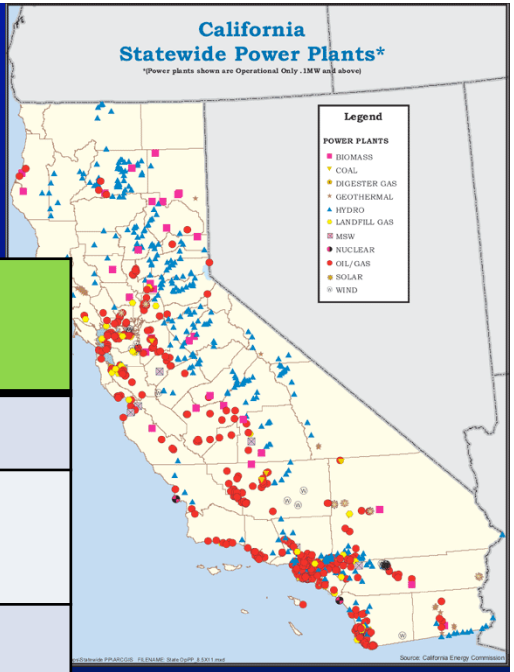
* 50% of this product is specifically purchased from individual suppliers.

** Percentages are estimate annually by the California Energy Commission based on electricity sold to California consumers during the previous year.

For specific information about this electricity product, contact Company Name. For general information about the Power Content Label, contact the California Energy Commission at 1-800-555-7794 or www.energy.ca.gov/consumer

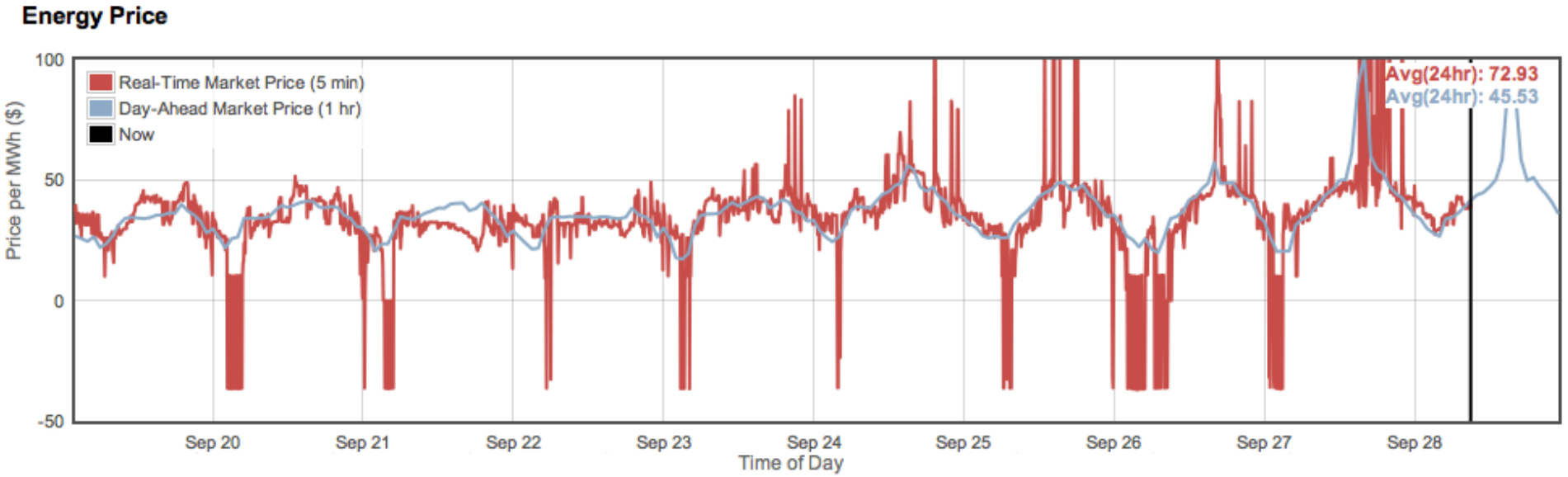
CA grid today - Supplies

Source	Rated (GW)	Capacity Factor[1]	Total Energy (TWh)	% of Total Energy
Geothermal	2.600	38.7%	8.68	3.8%
Biomass/ Biogas	1.145	43.5%	4.30	1.9%
Small Hydro	1.380	31.7%	3.77	1.7%
Wind	2.812	29.1%	7.06	3.1%
Solar[3]	0.403	28.7%	1.00	0.4%
Nuclear	4.456	85.9%	33.00	14.6%
Hydro	12.574	27.7%	30.05	13.3%
Imports	11.055[2]	66.6%	63.43	28.0%
Thermal	44.339	19.7%	75.43	33.3%
Total	80.764	32.6%	226.71	100.0%



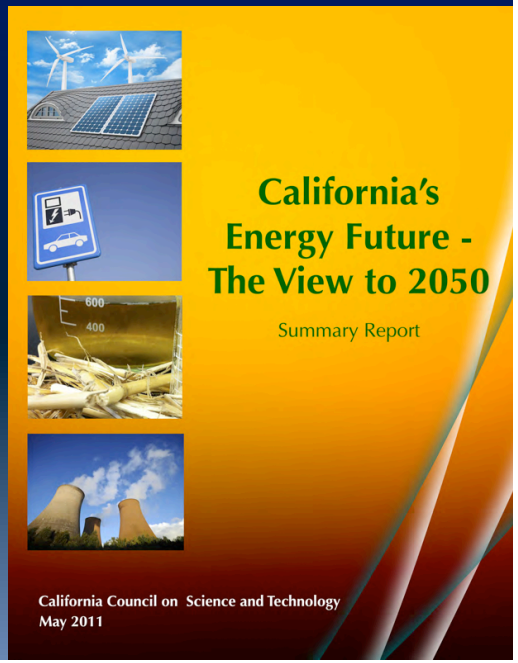
[1] Mean delivered power divided by rated power (excl. import)
[2] For imports, rating is the maximum observed power
[3] Residential net factored into demand

… and price


Energy Price
Real-Time Market Price (5 min)
Day-Ahead Market Price (1 hr)
Now
Avg(24hr): 72.93
Avg(24hr): 45.53
Price per MWh ($)
100
50
0
-50
Sep 20
Sep 21
Sep 22
Sep 23
Sep 24
Sep 25
Sep 26
Sep 27
Sep 28
Time of Day

Quantifying Sustainability - CA Law

- AB 32
  - Reduce GHG emissions to 1990 levels by 2020
- Governor's executive order S-3-05 (2005)
  - 80% reduction below 1990 levels by 2050
- Renewable Portfolio Standard
  - 33% renewables by 2020,
  - 20% biopower procurement
- 480 => 80 mmT CO2e in 40 years
  - Population: 37 => 55 million
  - Economic growth



CA2050: GHG 90% below 1990

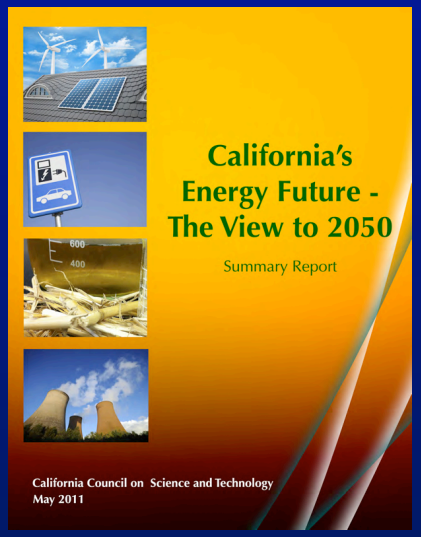
The short answer: **Yes, we can**

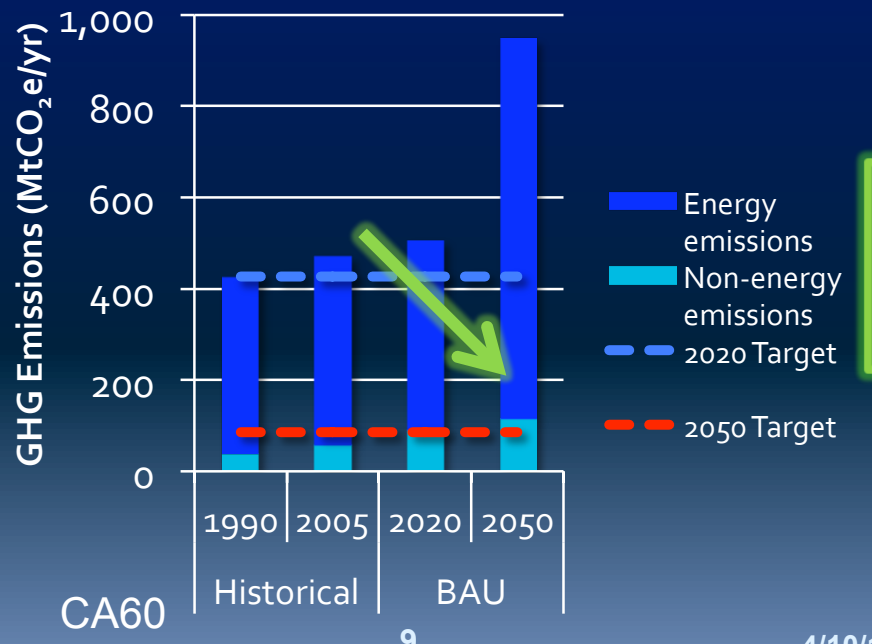
- We can achieve 80% cuts in emissions and still meet our energy needs.
- We can get ~60% of the cuts with technology we largely know about.
  - We basically know how to do this
  - A lot of this technology is in demonstration.
    - Deployment will depend on policy and innovation.
    - Note: We excluded extremely expensive technology
- We can get the rest of the cuts to 80% below 1990, but this will require new technology innovation and development.

CHAIR'S LECTURE:
CALIFORNIA ENERGY FUTURES STUDY RESULTS
July 15, 2011

Jane C. S. Long

But, …





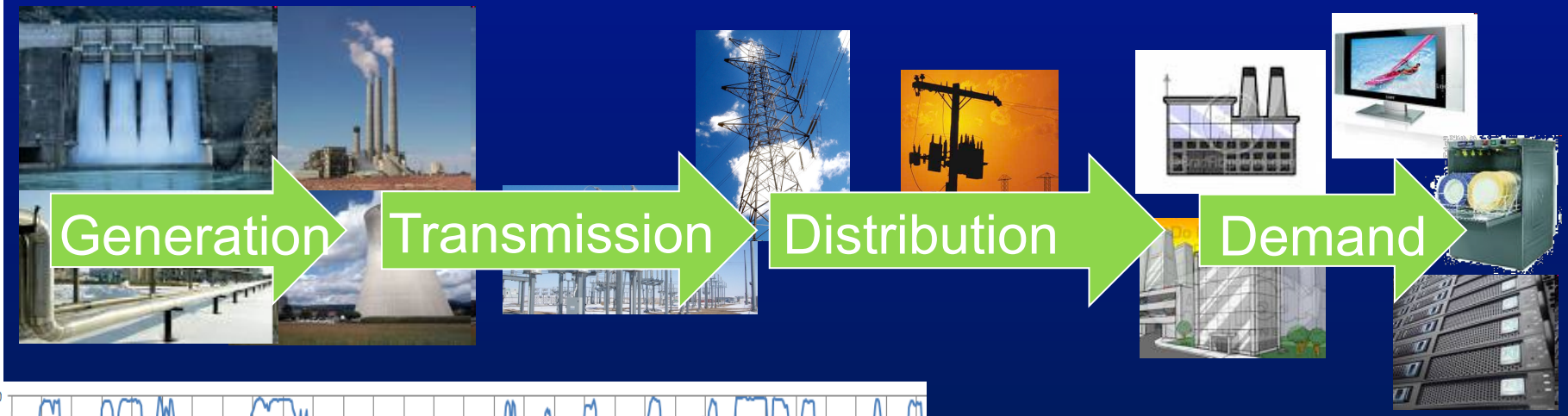
Two major technology limitations will cause us to exceed the target:

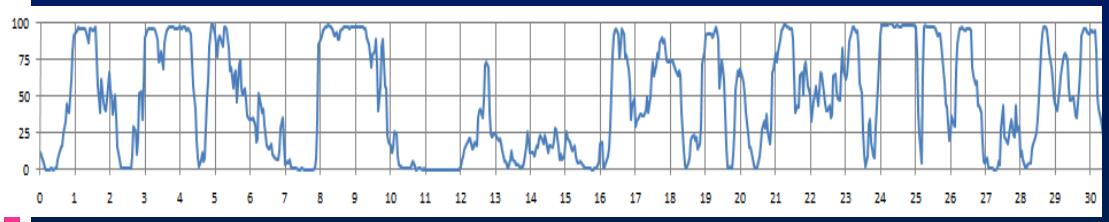
- We don't have sufficient technology for load balancing without emissions
  - This is an especially big deal if we don't have baseload power
- We don't have enough technology choices "in the pipeline" for de-carbonizing fuel.
  - Need advanced biofuels, but it likely won't be enough
  - CCS may play a larger role in fuels than in electricity

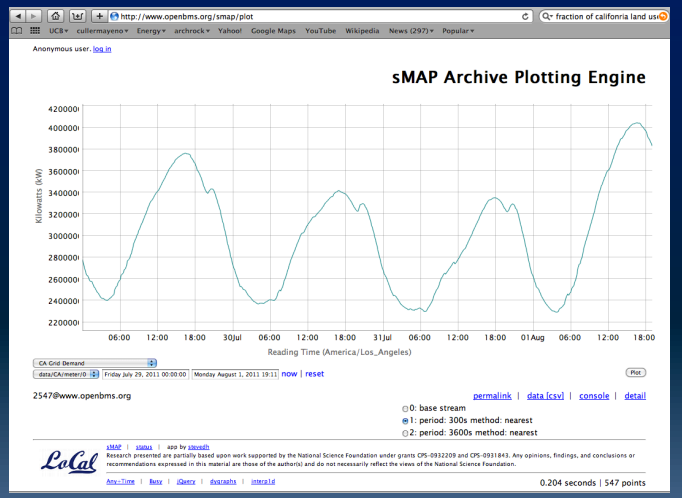
The Problem: Supply-Demand Match

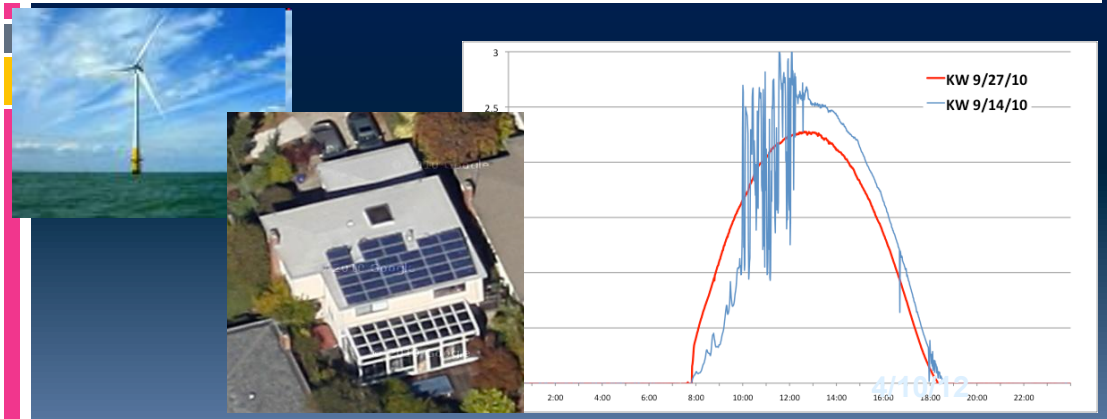
Baseline + Dispatchable Tiers

Oblivious Loads









CA60

To 2050 … Scenarios

Nuclear
62% nuclear
44GW
33% renewables
5% natl gas
load balancing

Fossil/CCS
62% fossil/CCS
49 GW
33% renewables
5% natl gas load
balancing

Renewables
90% renewables
(70% intermittent)
160 GW
10% natl gas
load balancing

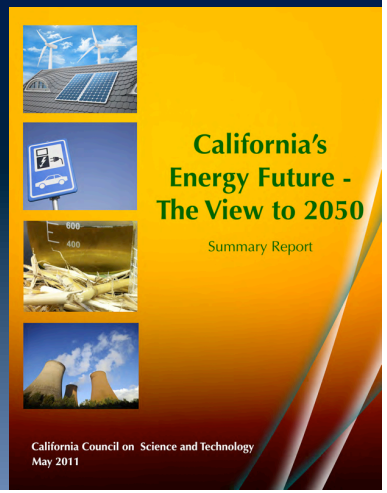
New Nuclear plant every 14 months for 40 years

New CCS facility every 9 mo. Exceeds saline aquifer

Resources exist
- 1.4 % of CA land
- 43% agriculture
- 3.4% urban

Zero Emissions Load Balancing (ZELB)

- Just the emissions from the natural gas used to *firm* the 33% renewables exceeds 2050 GHG target
- Even with 50% with natural gas & 50% with some yet-to-exist storage tech.



Towards an 'Aware' Energy Infrastructure

Baseline + Dispatchable Tiers

Oblivious Loads











Generation → Transmission → Distribution → Demand

LoCal

Non-Dispatch Sources

Aware Interactive Loads












Communication

Communication

Limits to Renewable Penetration

- Variability, Intermittency of Supply

- Visibility into Availability of Supply
- Ability of Loads to Adapt
- Algorithms and Techniques for Reactive Load Adaptation

- Capability of the Infrastructure to maintain the match

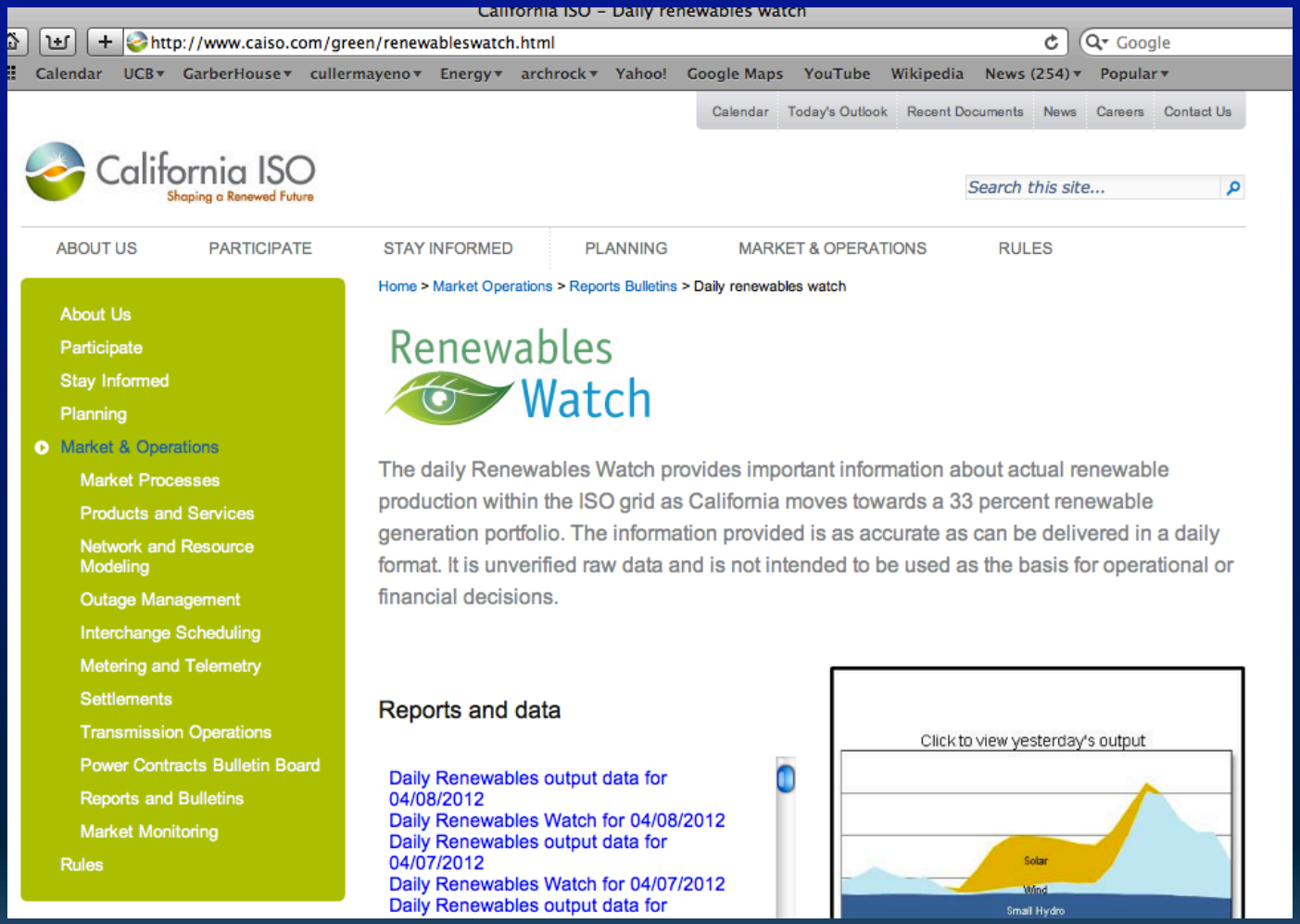
ZELB

- More challenging for the maximum renewables case
  - GW-days of storage needed
  - Smart grid solution is a challenge
    - Smart meter fiasco
    - Completely change business model to demand follows load vs load follows demand
    - Need whole different system of system control – but will this ever solve the GW-day problem?
- Would be easier to have significant baseload power
  - No more hydro likely
  - Renew interest in geothermal energy
  - Choose nuclear or CCS

CHAIR'S LECTURE: CALIFORNIA ENERGY FUTURES STUDY RESULTS
July 15, 2011

Jane C. S. Long

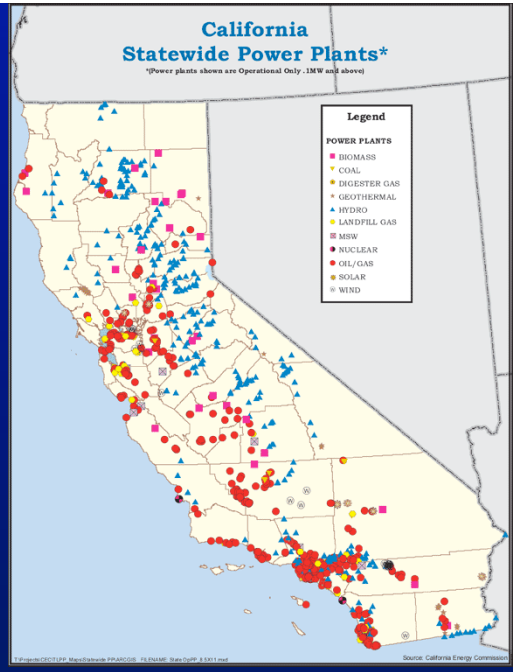
New visibility into the CA grid

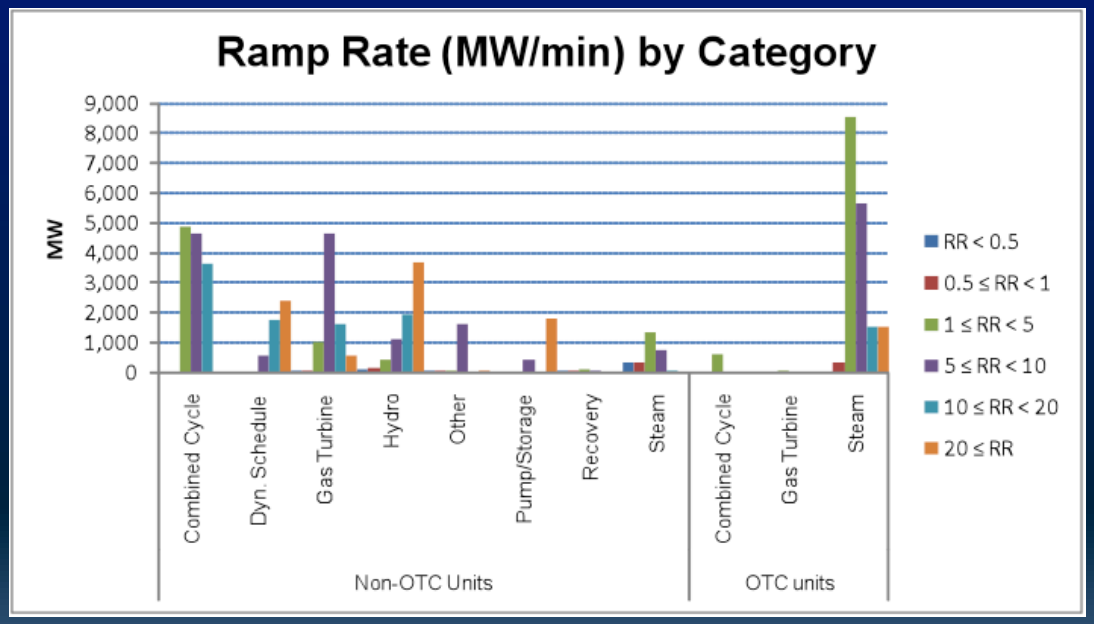


- http://www.caiso.com/green/renewableswatch.html

Data Sources

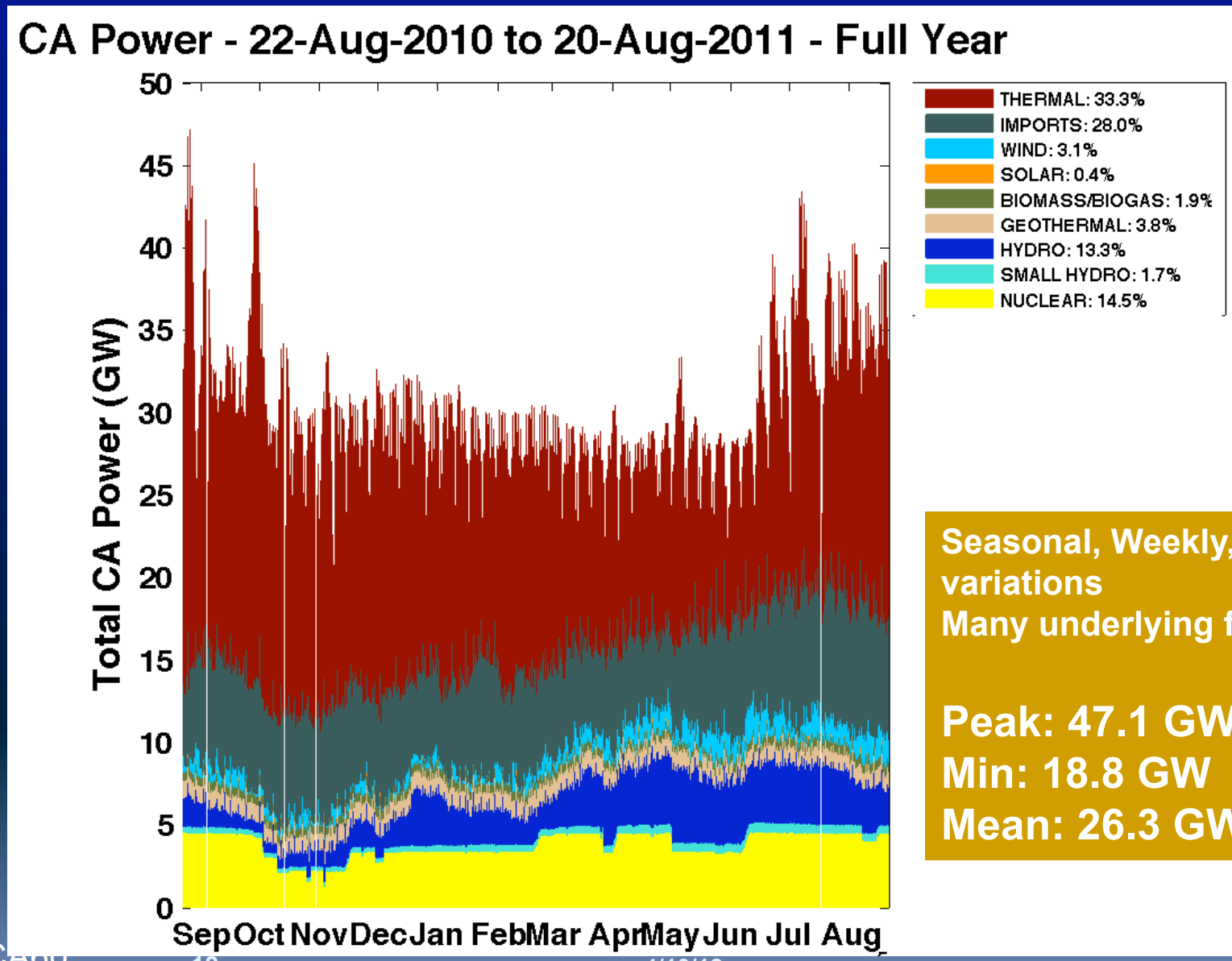
- CA generation plant locations, type, and rated power (> 0.1 MW) [CEC]
- Hourly output from each type of CA generation source for > 1 year [CAISO]





[CEC] http://energyalmanac.ca.gov/powerplants/Power_Plants.xls
[CAISO] http://www.caiso.com/green/renewableswatch.html

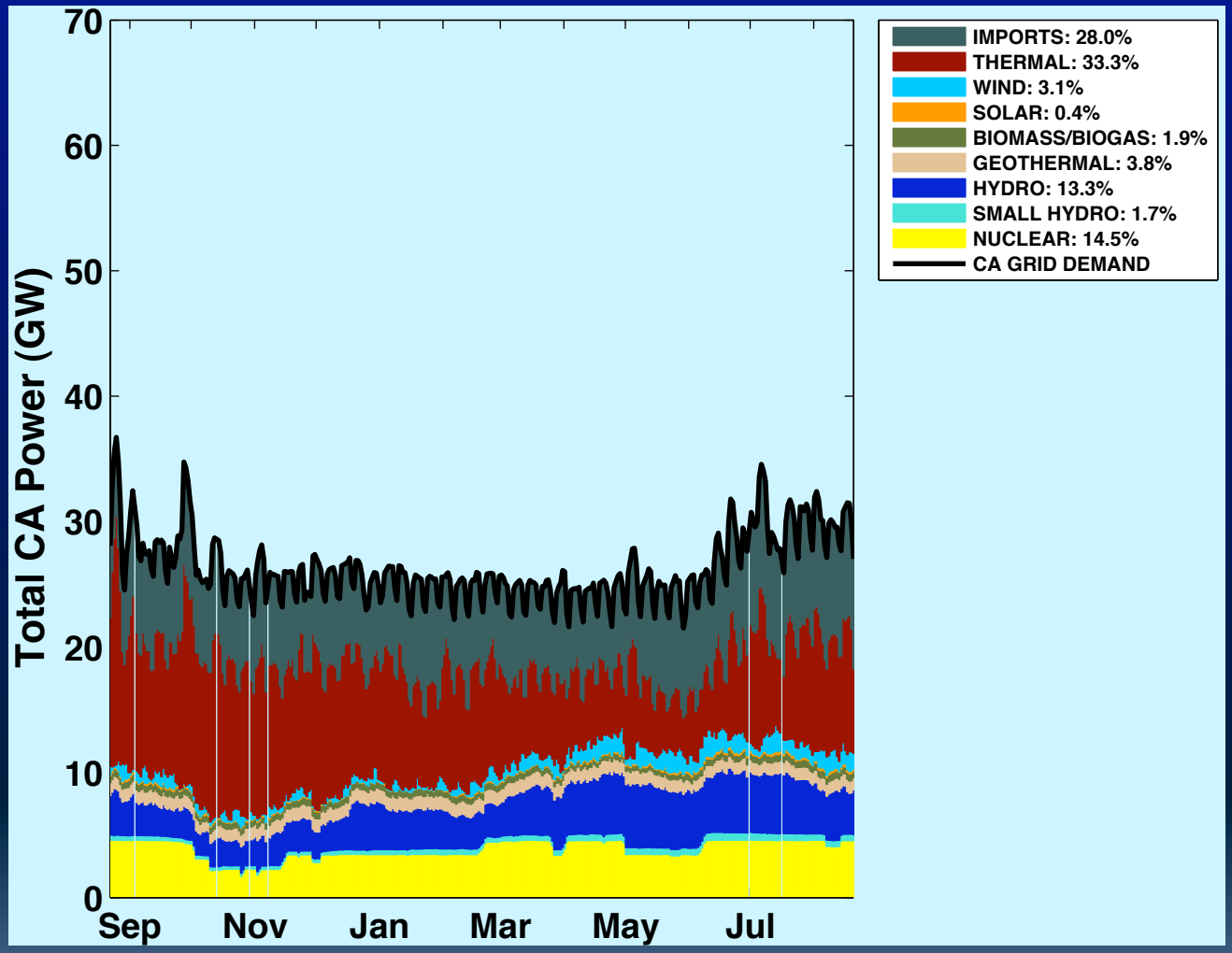
A year in the today's grid



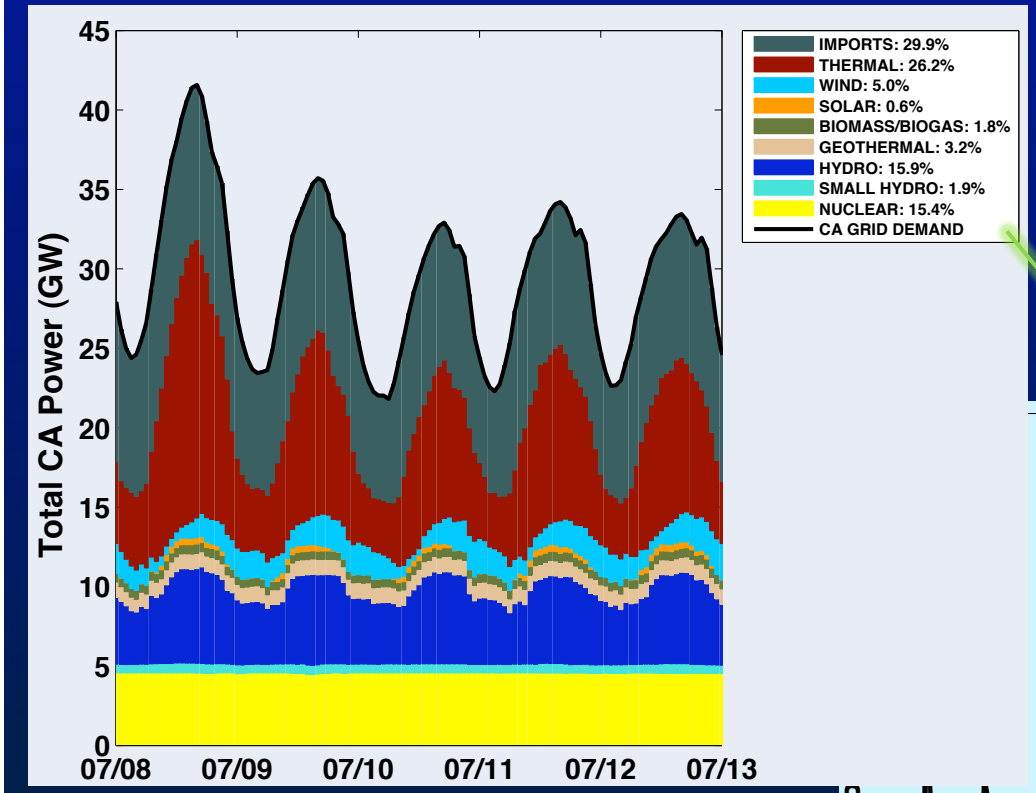
Seasonal, Weekly, Daily variations
Many underlying factors

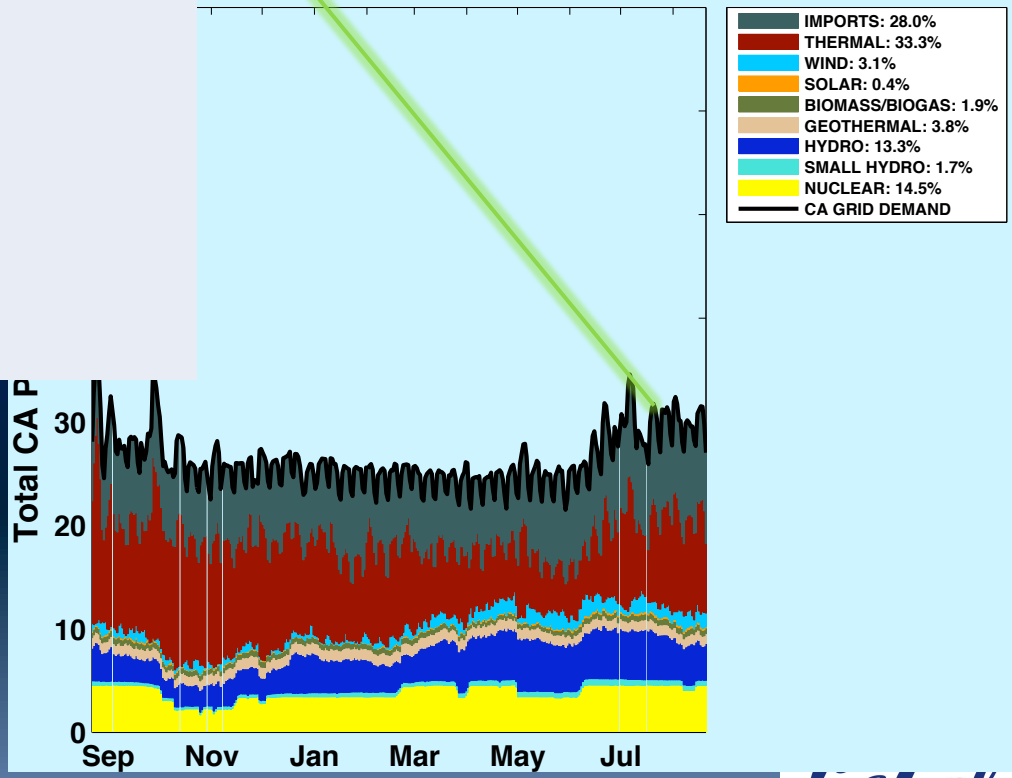
Peak: 47.1 GW
Min: 18.8 GW
Mean: 26.3 GW

A year … daily averages

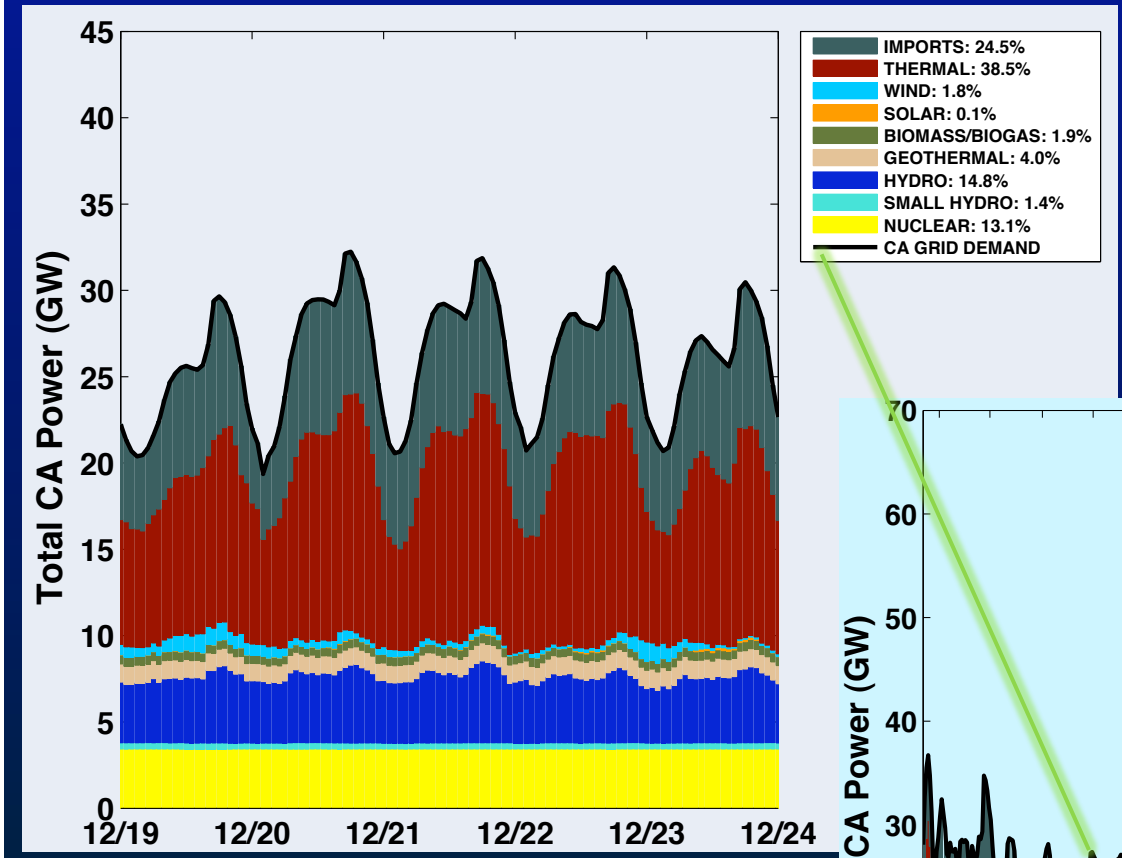


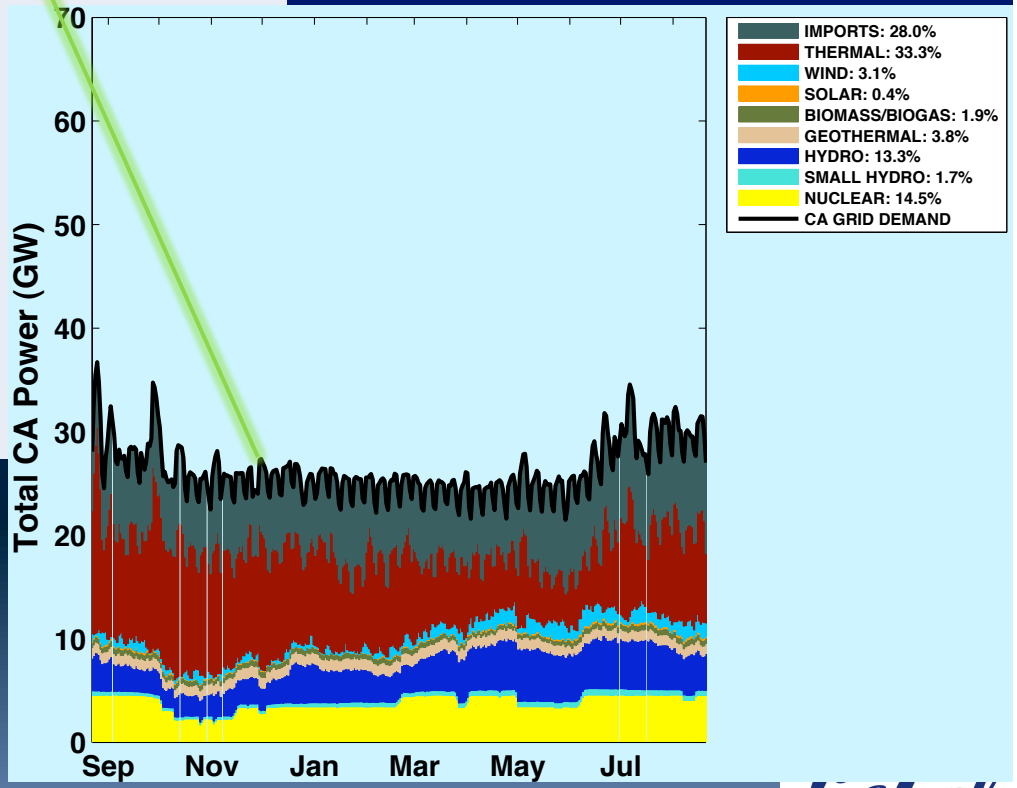
A mid-summer's week



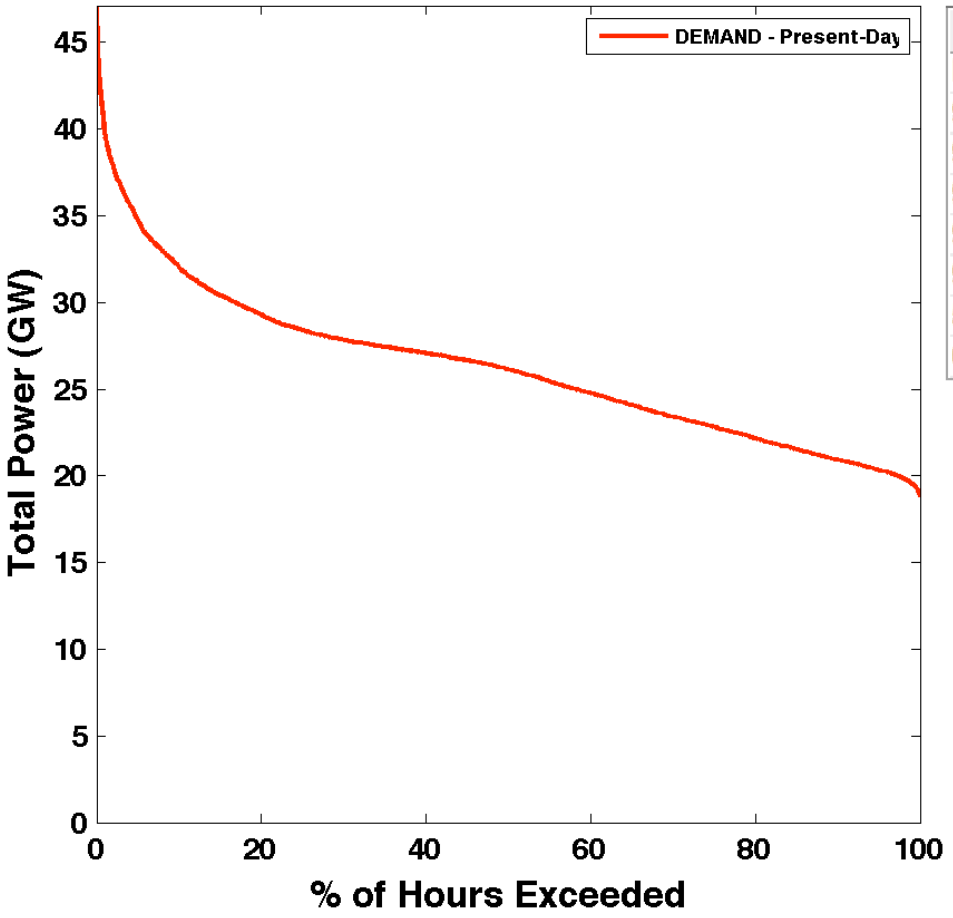


A winter week's tale



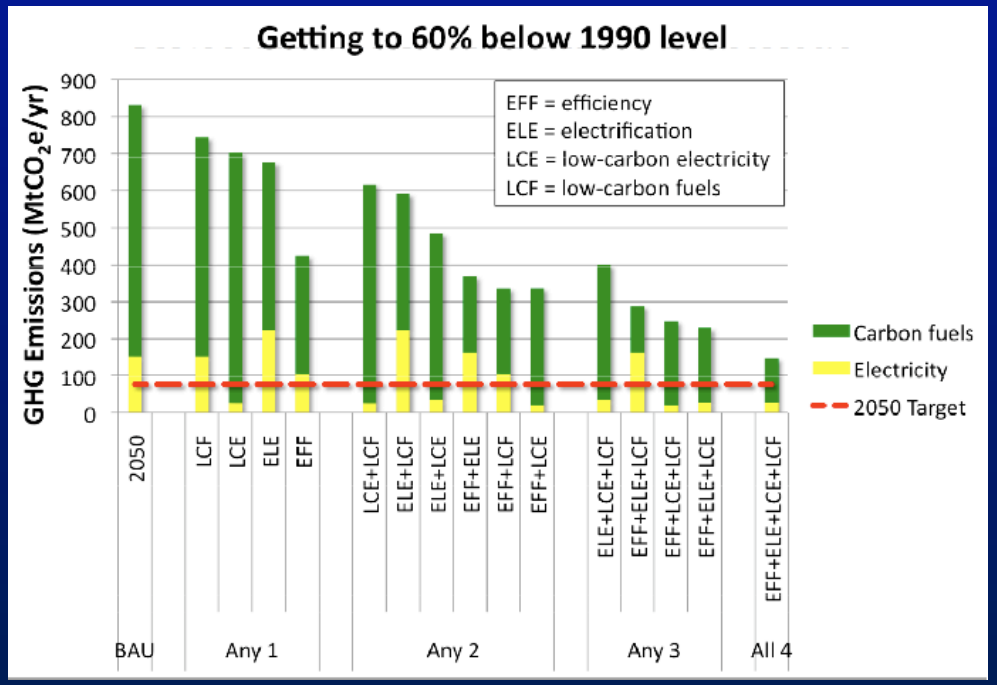


The Demand Duration Curve



%Hrs	GW
Max	47.128
99.9	45.398
99.5	42.373
99.0	39.786
95.0	34.846
90.0	32.086
50.0	26.173
0.0	18.792

Method for Understanding change?

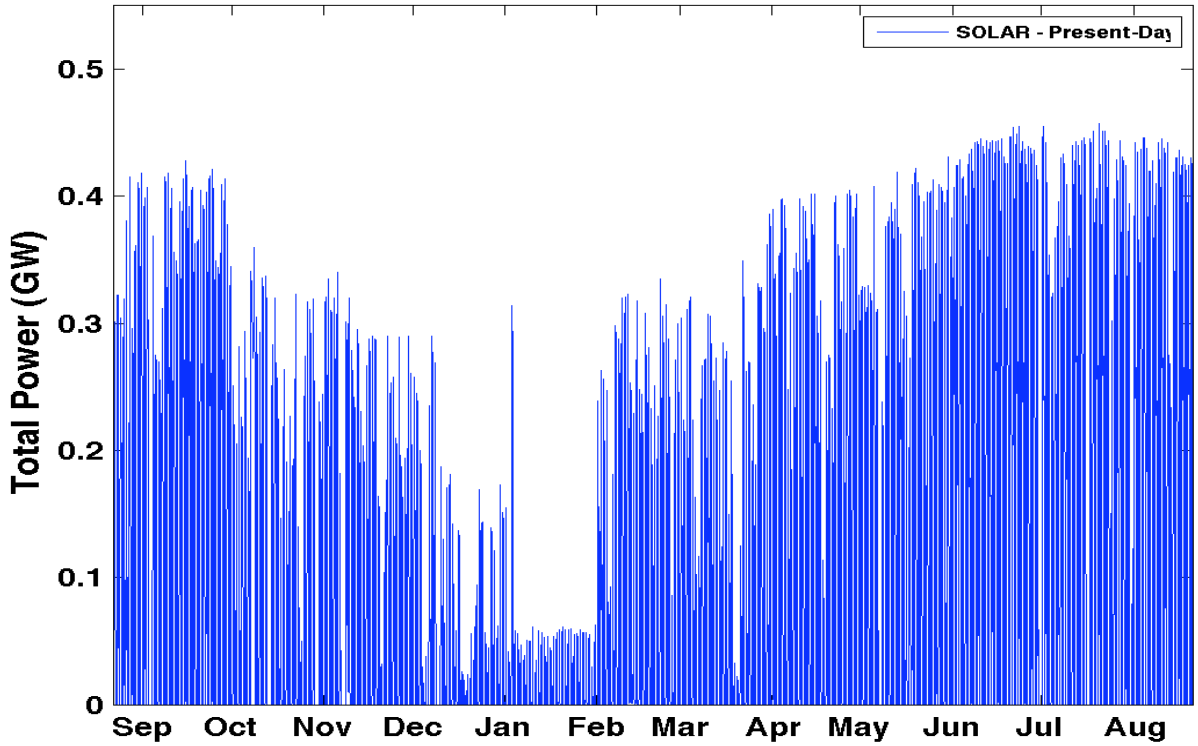


- Statistical summaries and rules of thumb
- Growth rates
  - population, economic activity, portfolio
- Technological innovation

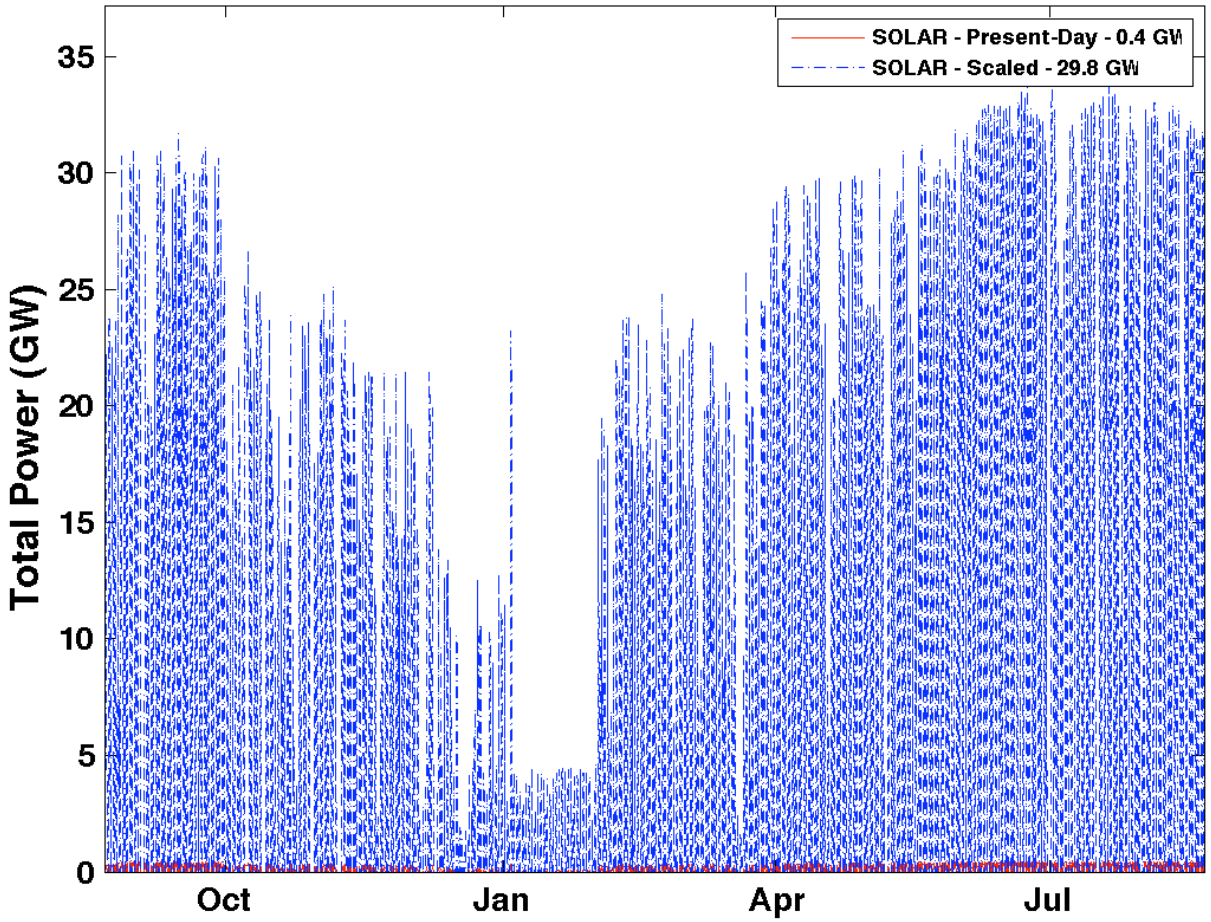
A Simpler "what if"

- Take current demand, current activity, current technology, current deployment
- At a crude top-level scale (by category)
  - Represented by the time series
- Scale up the renewable portions
  - Preserve the seasonal, weekly, daily, hourly effects of mother nature *
- Scale back the fossil fuel based supplies
- With current demand as a reference

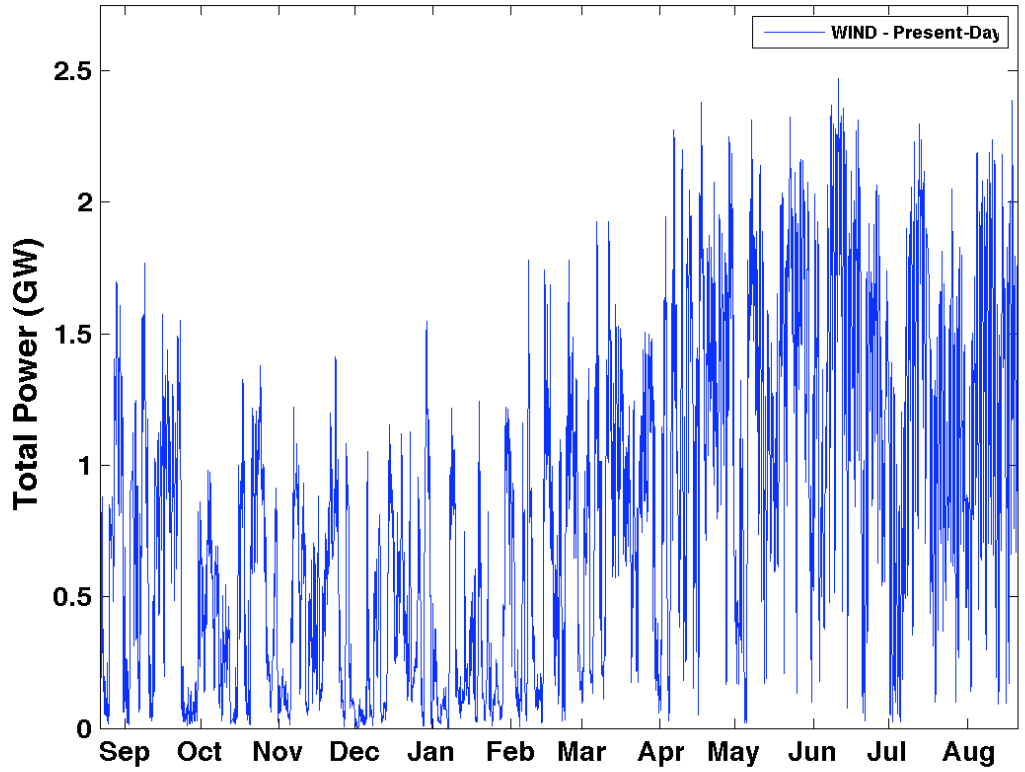
Example: Solar



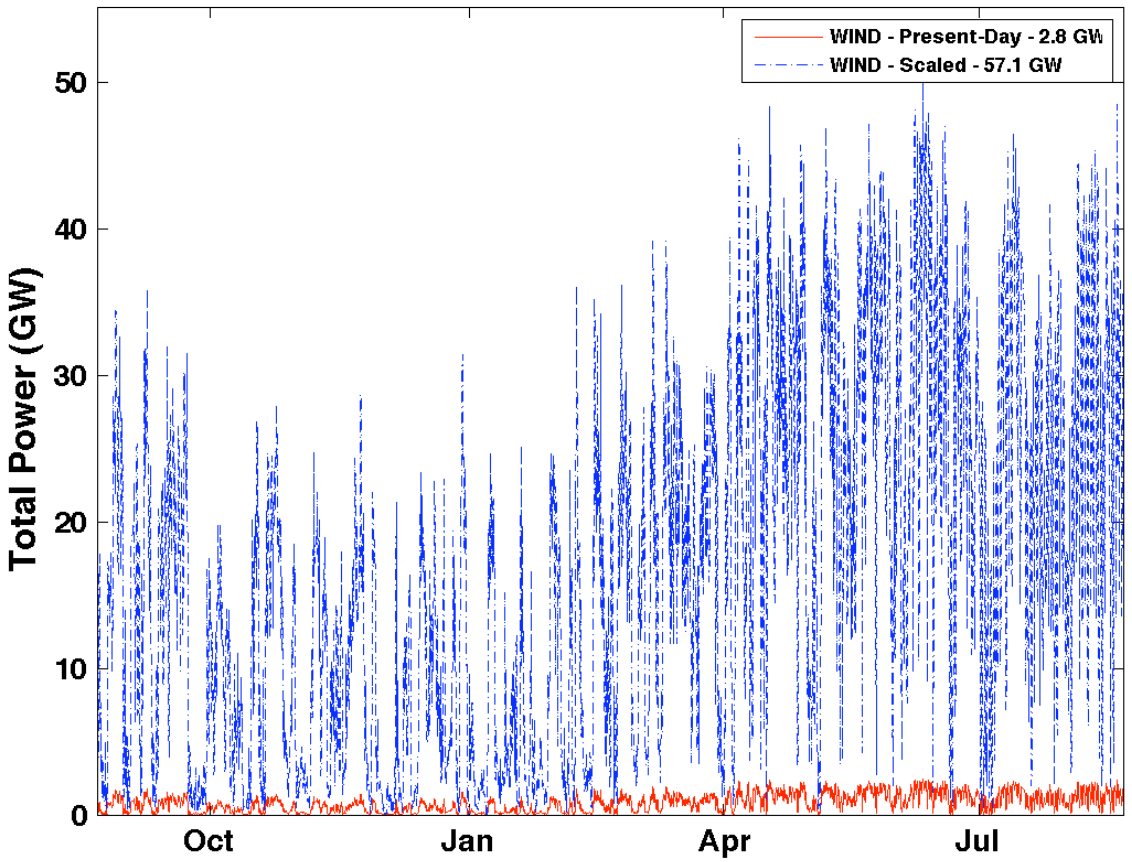
Example: Solar Scaled



Example: Wind



Wind - Scaled


WIND - Present-Day - 2.8 GW
WIND - Scaled - 57.1 GW
Total Power (GW)
0
10
20
30
40
50
Oct
Jan
Apr
Jul

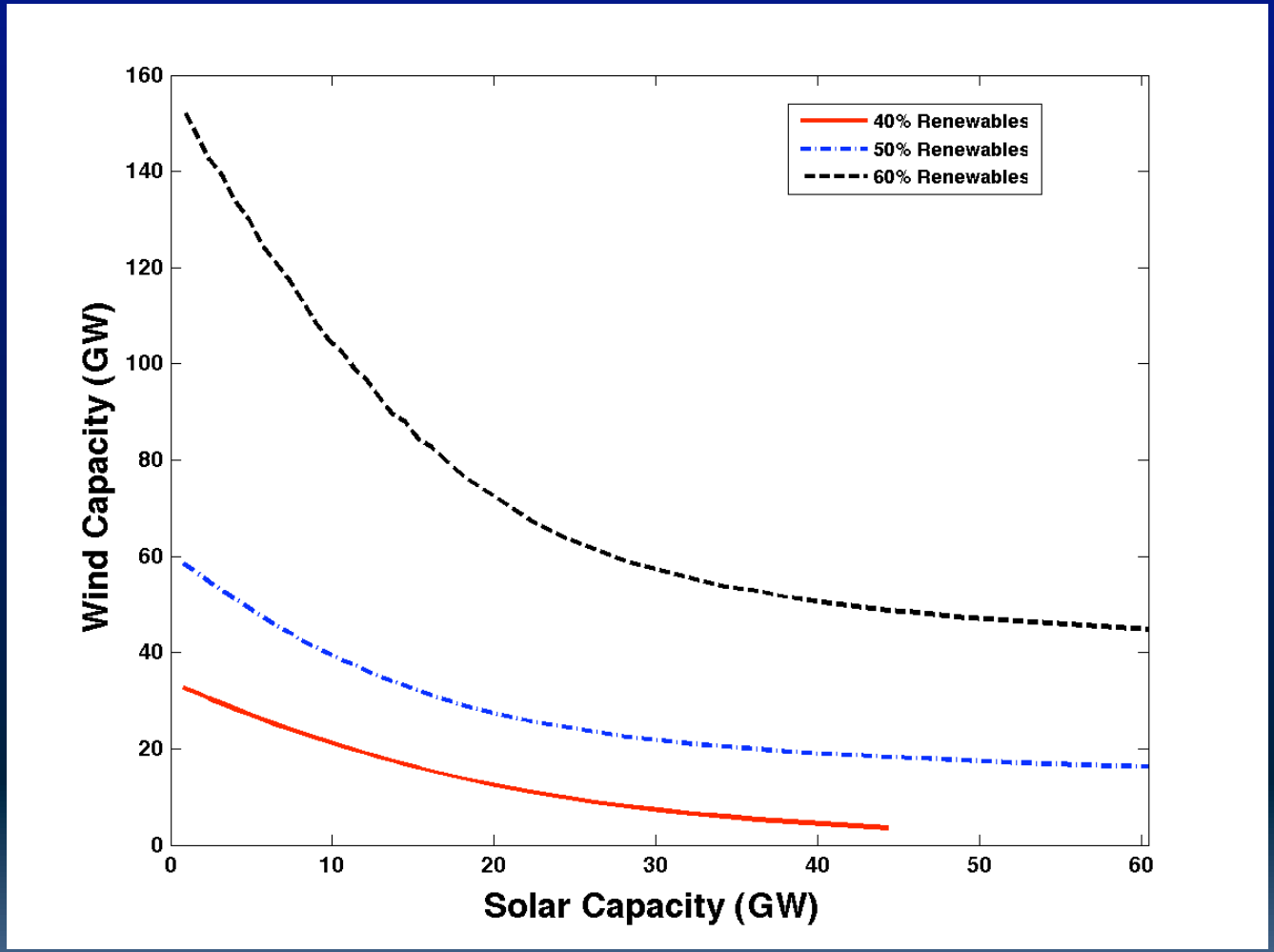
Caveats

- Captures dynamics as reflected in current design and deployment of these assets
  - Orientation, geographic diversity, weather, …
- Does not reflect deeper constraints
  - Transmission capacity, …
- Top level analysis of dynamics
  - Needs to be repeated at successively finer levels

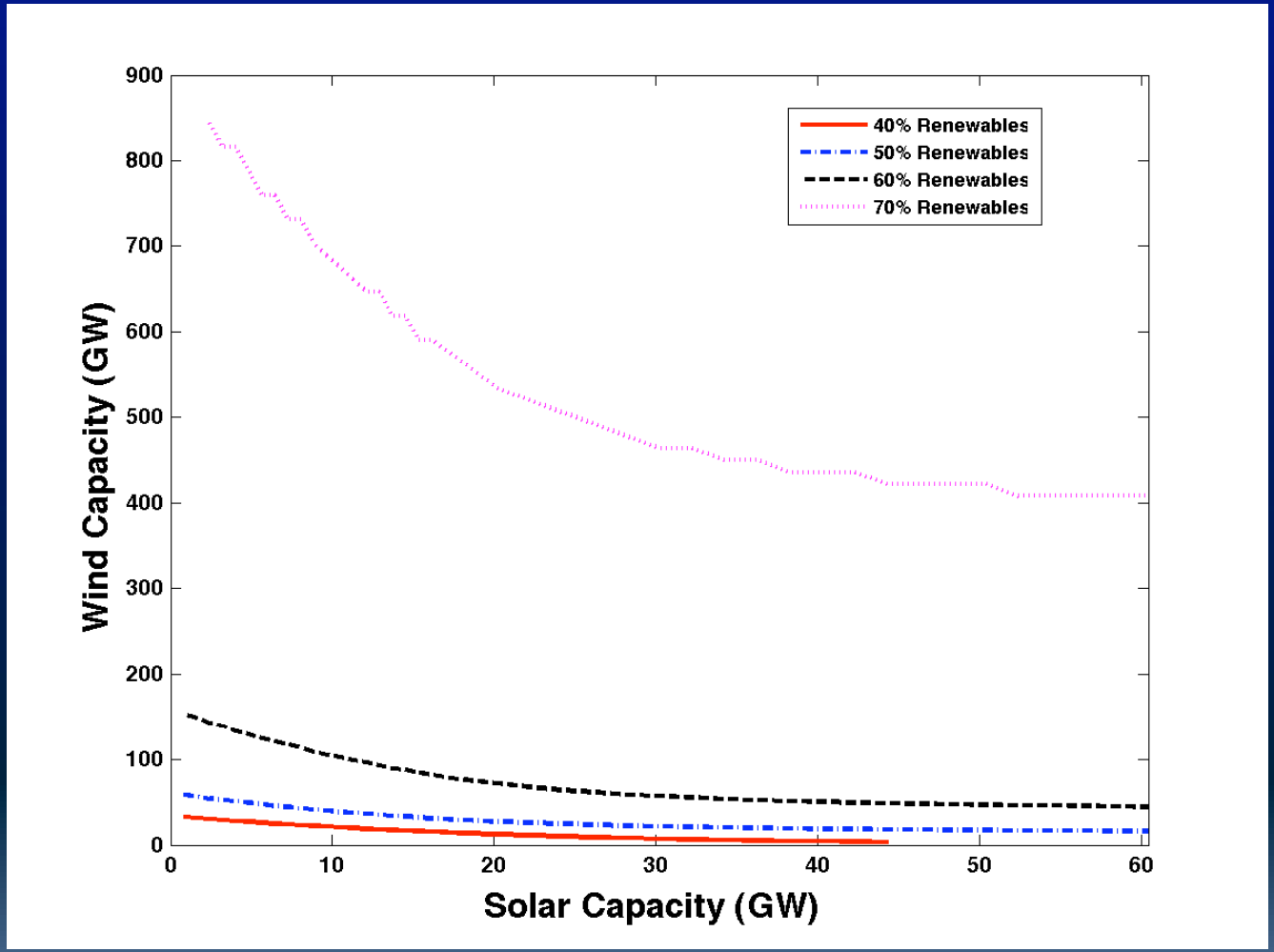
How much to scale each?

- Scaling of renewables depends on how availability interacts with demand
- At all timescales
- Find minimum combined capacity (cost?) that achieves a target penetration
  - Utilized energy with current demand

Joint Wind/Solar Scaling

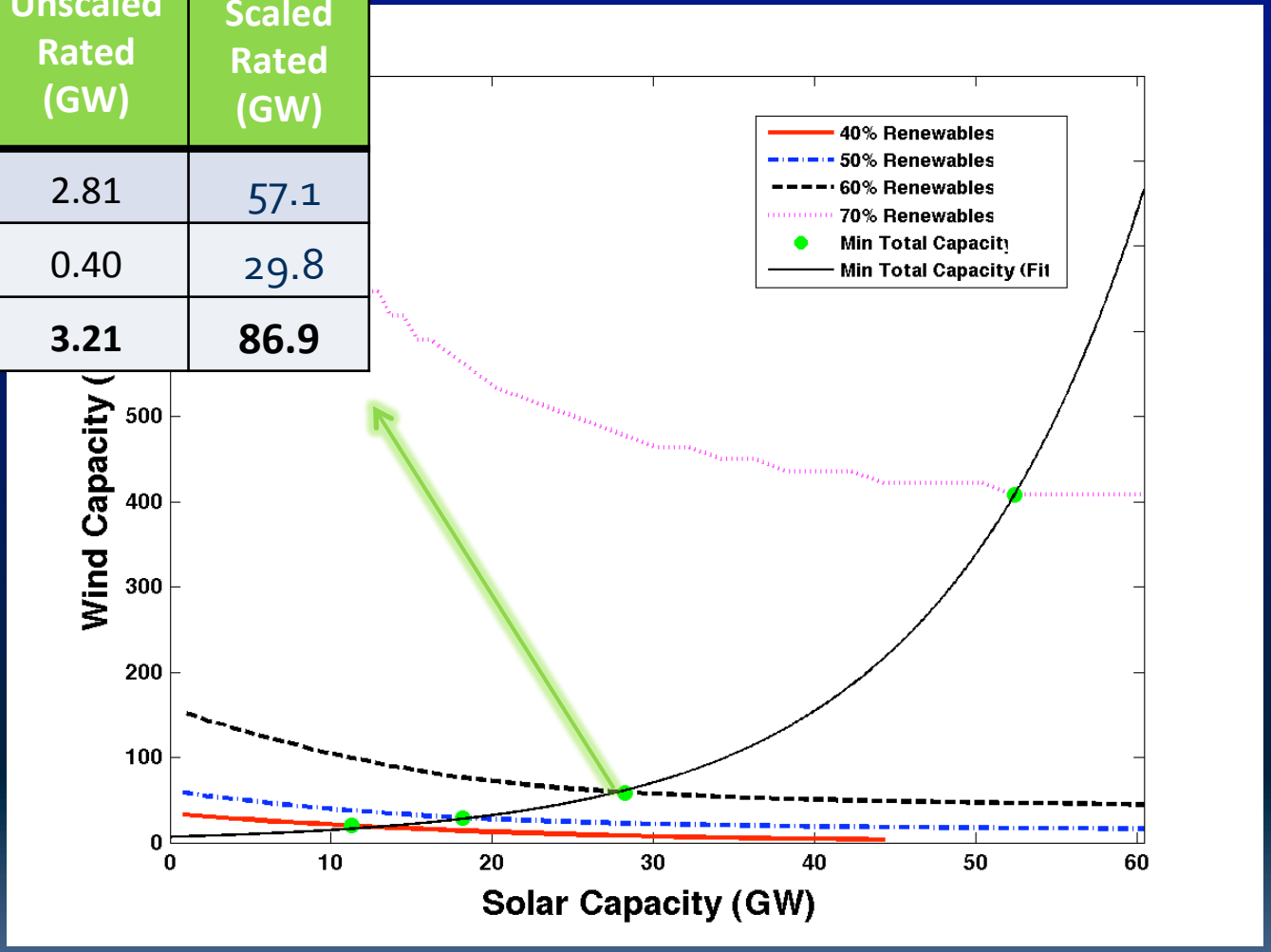


Joint Wind/Solar Scaling



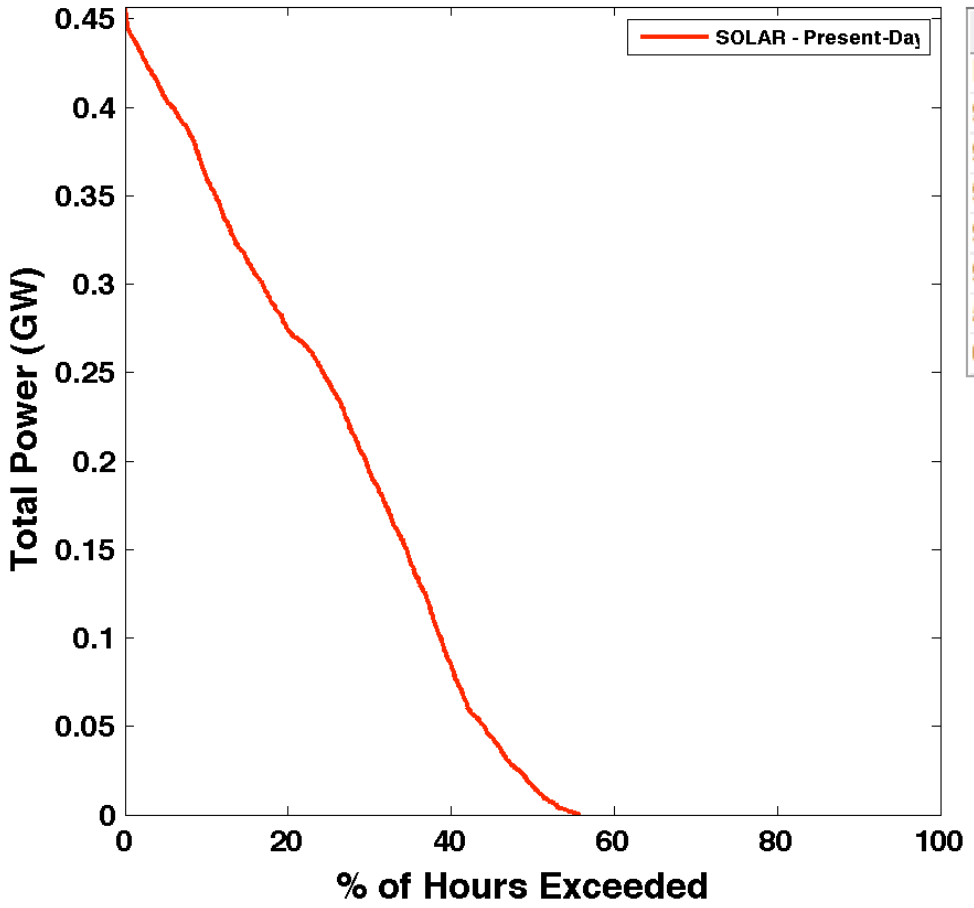
Joint Wind/Solar Scaling

Source	Unscaled Rated (GW)	Scaled Rated (GW)
Wind	2.81	57.1
Solar	0.40	29.8
TOTAL	**3.21**	**86.9**



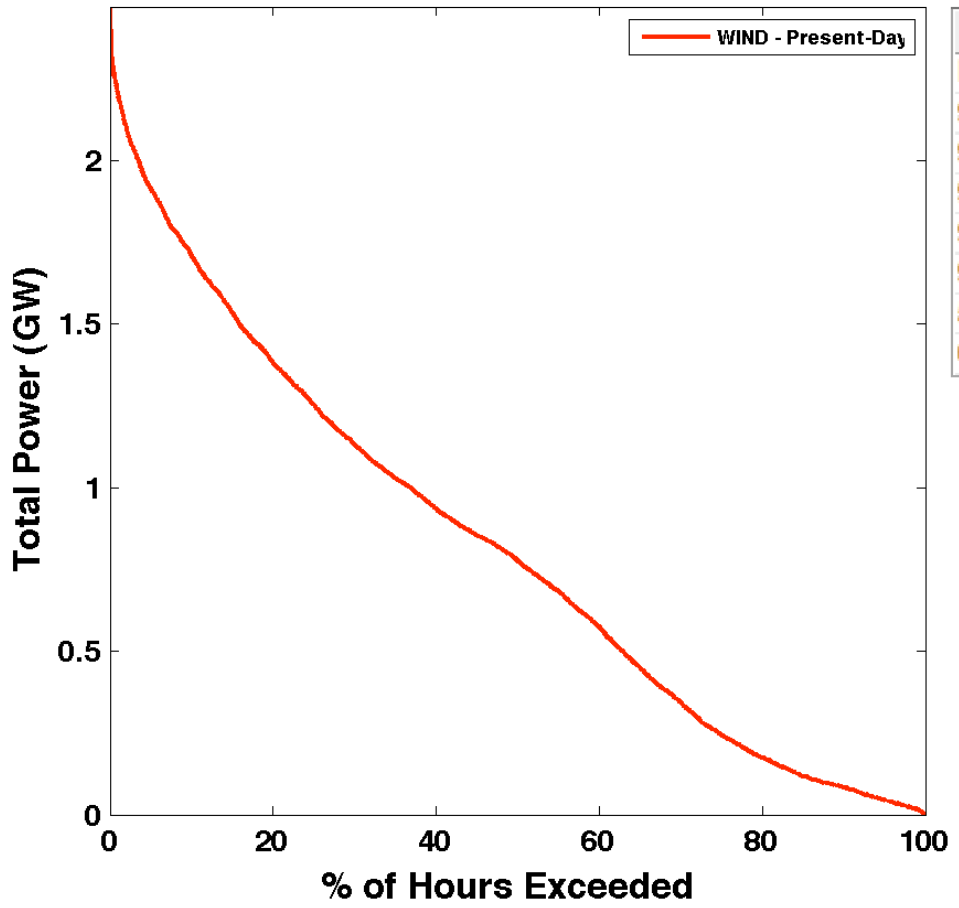
Why?

Solar Duration Curve



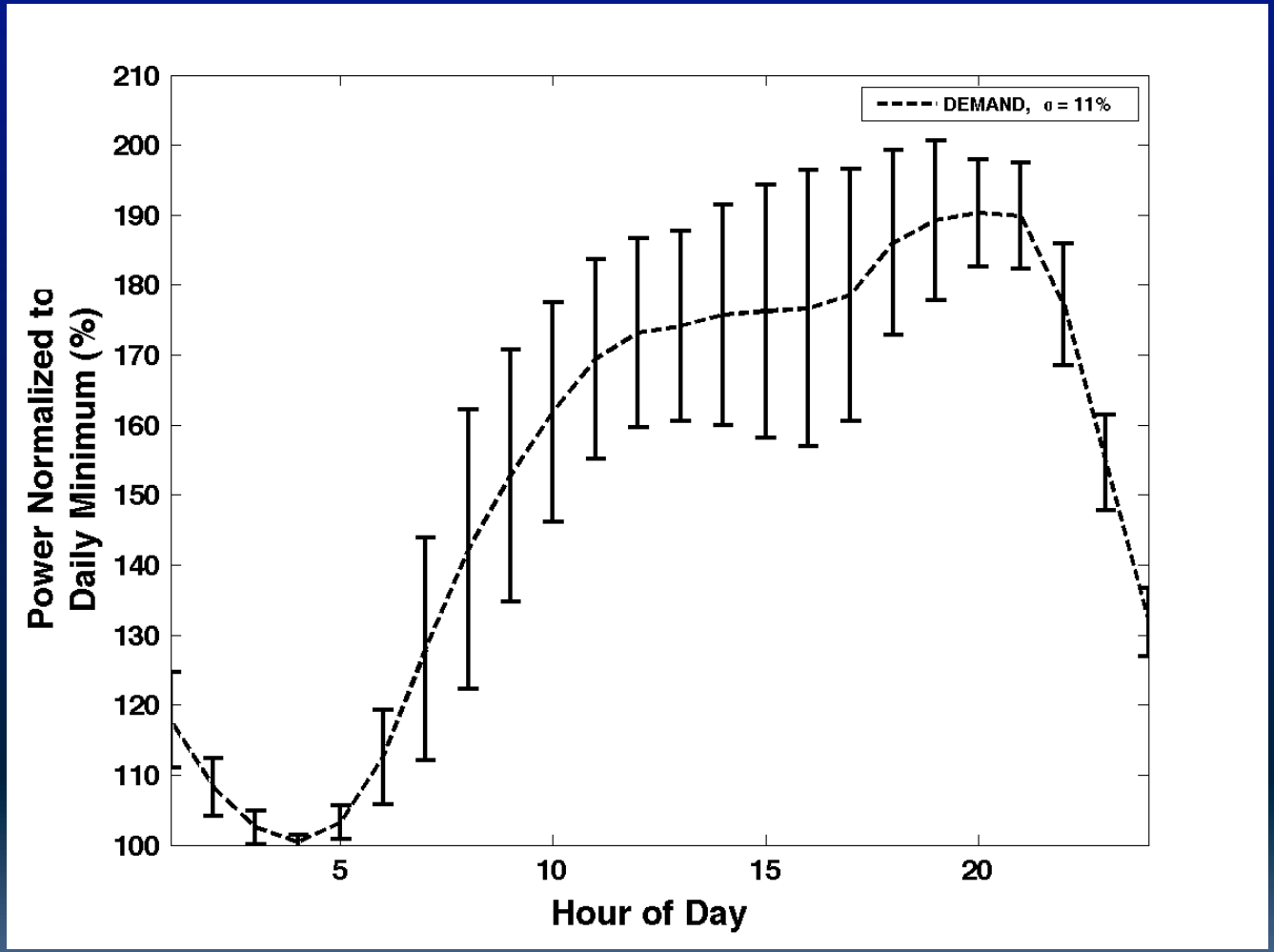
%Hrs	GW
Max	0.457
99.9	0.453
99.5	0.444
99.0	0.440
95.0	0.405
90.0	0.361
50.0	0.017
0.0	0.000

Wind Duration Curve

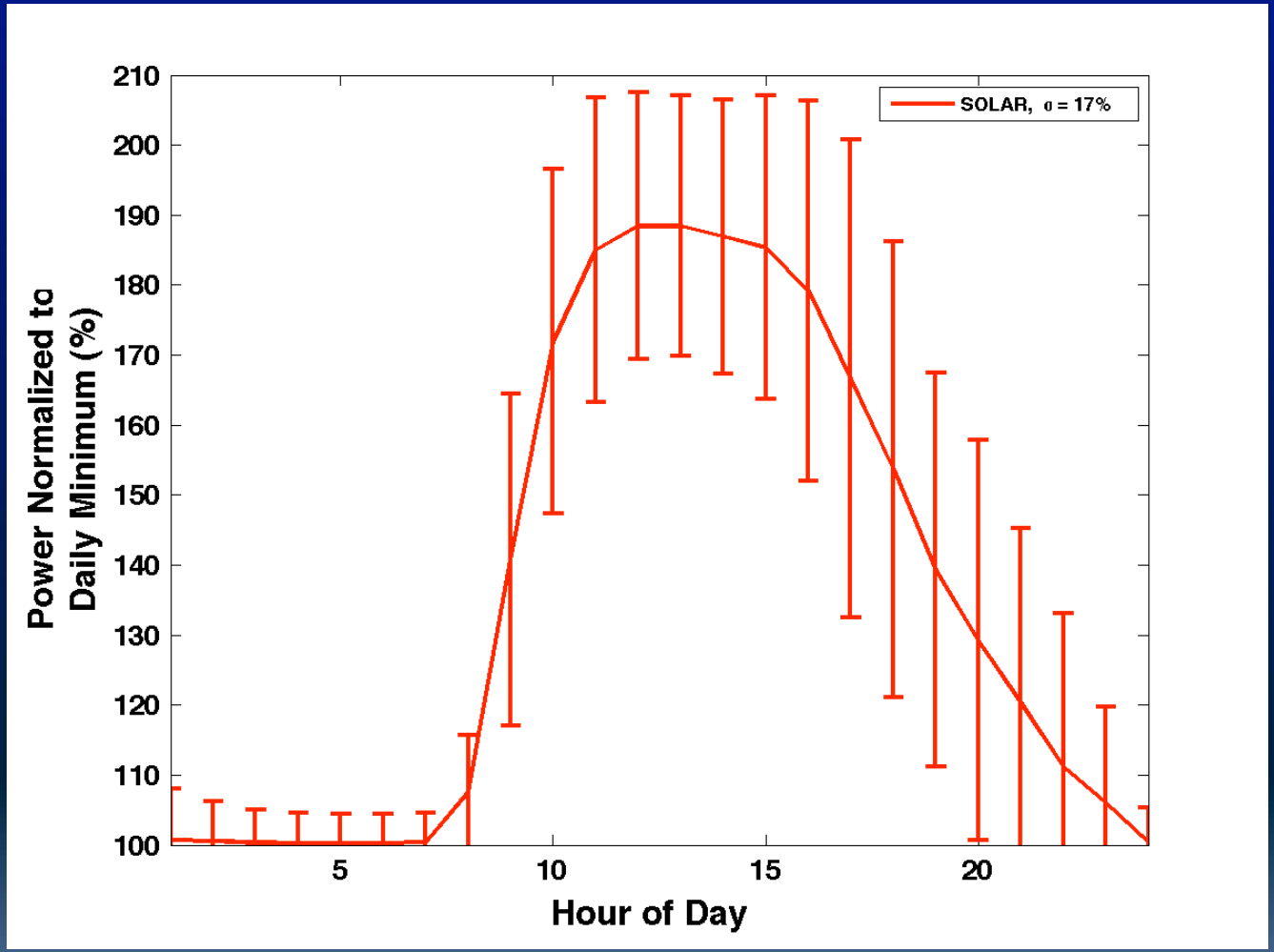


%Hrs	GW
Max	2.470
99.9	2.380
99.5	2.270
99.0	2.199
95.0	1.916
90.0	1.714
50.0	0.779
0.0	0.002

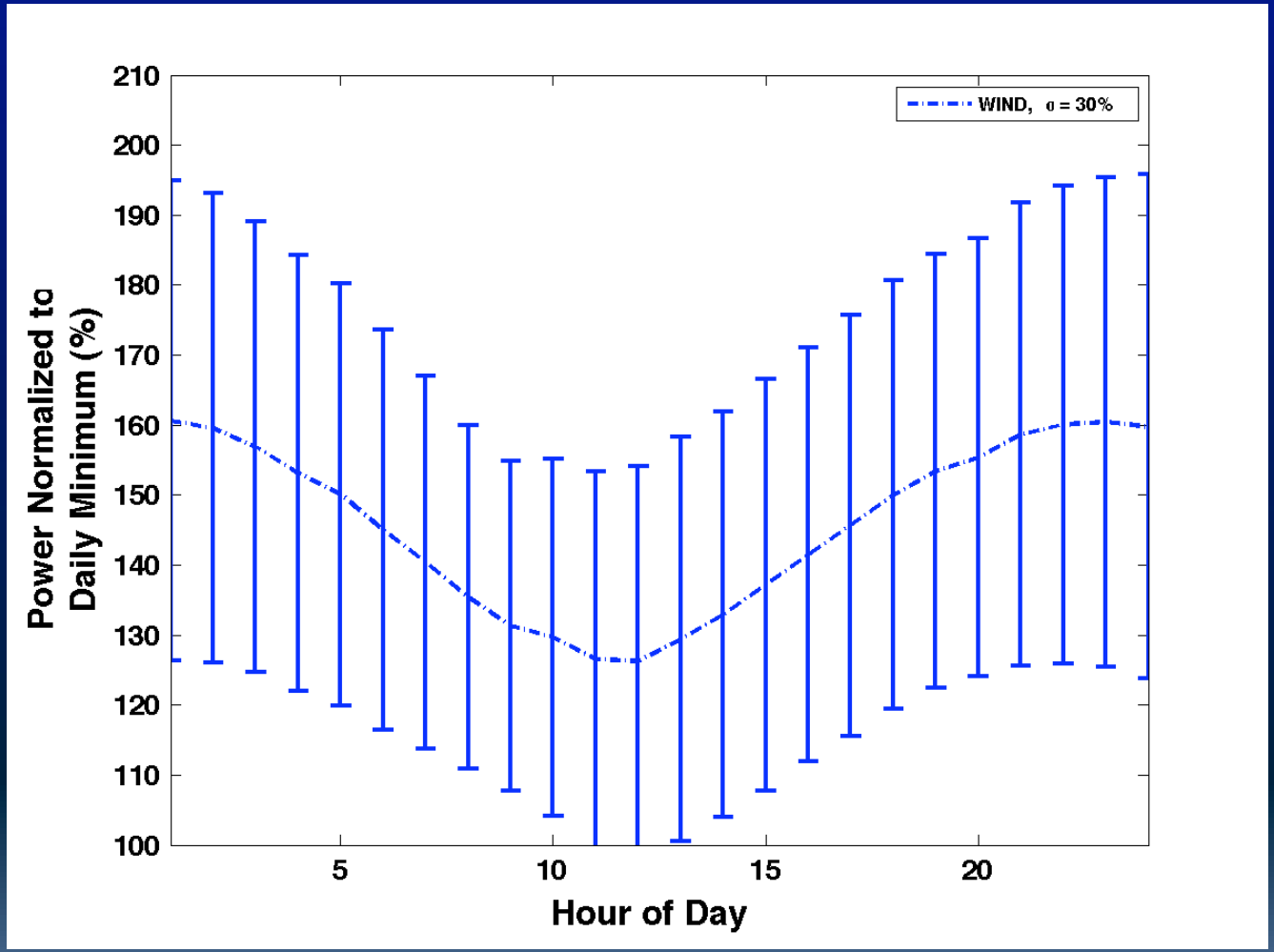
Daily Demand Pattern



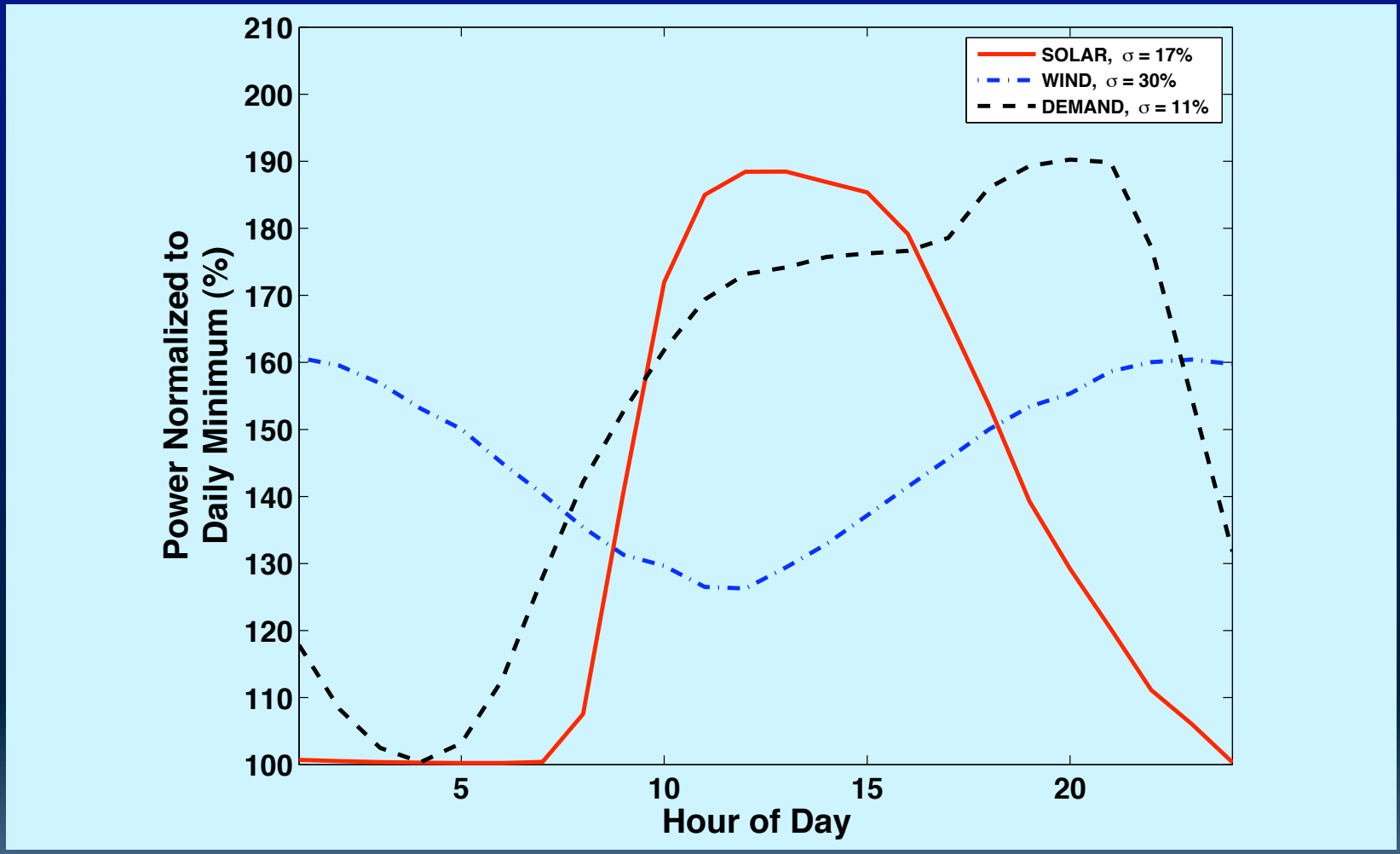
Daily Solar Pattern



Daily Wind Pattern

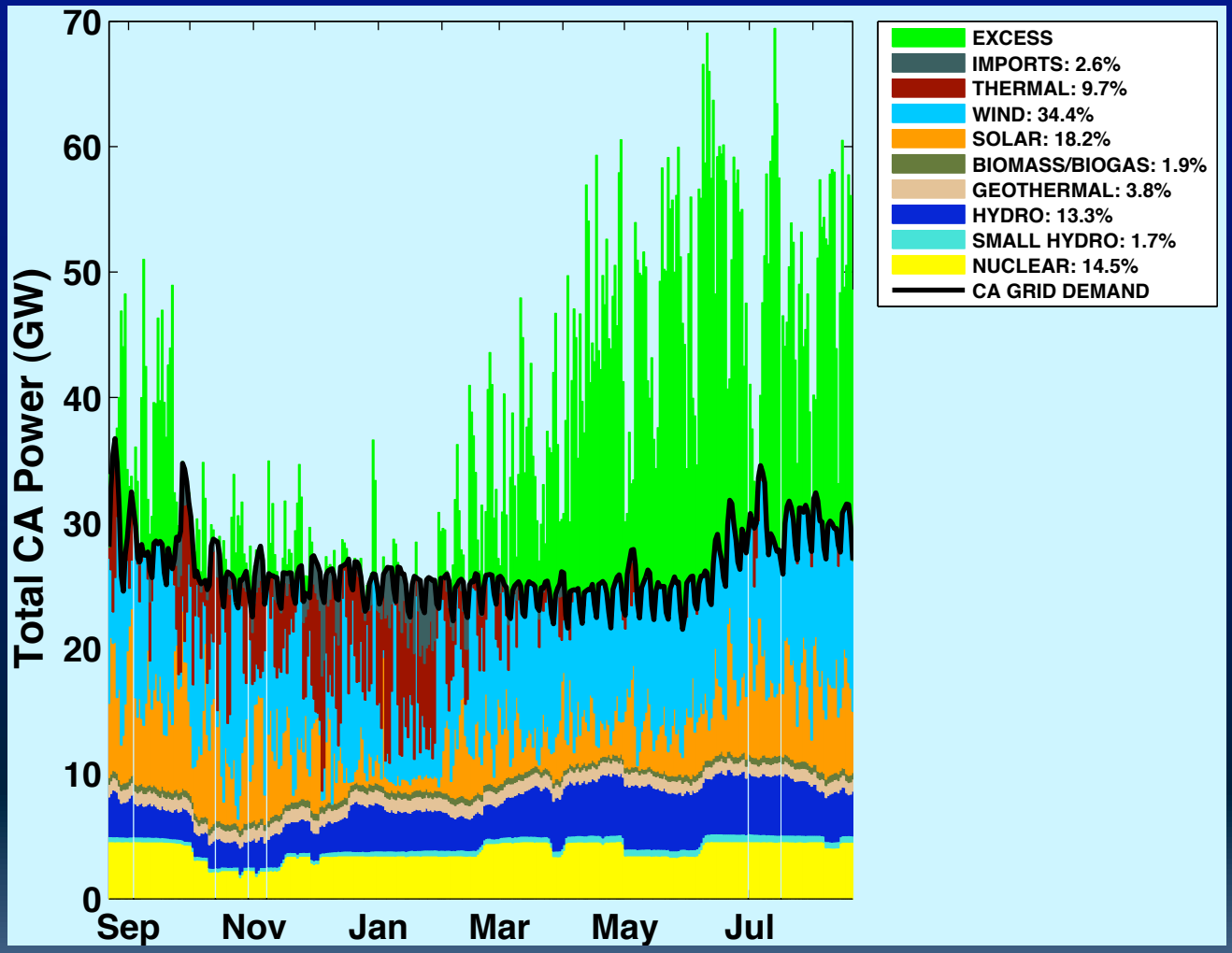


Relationship of Daily Pattern (mean)

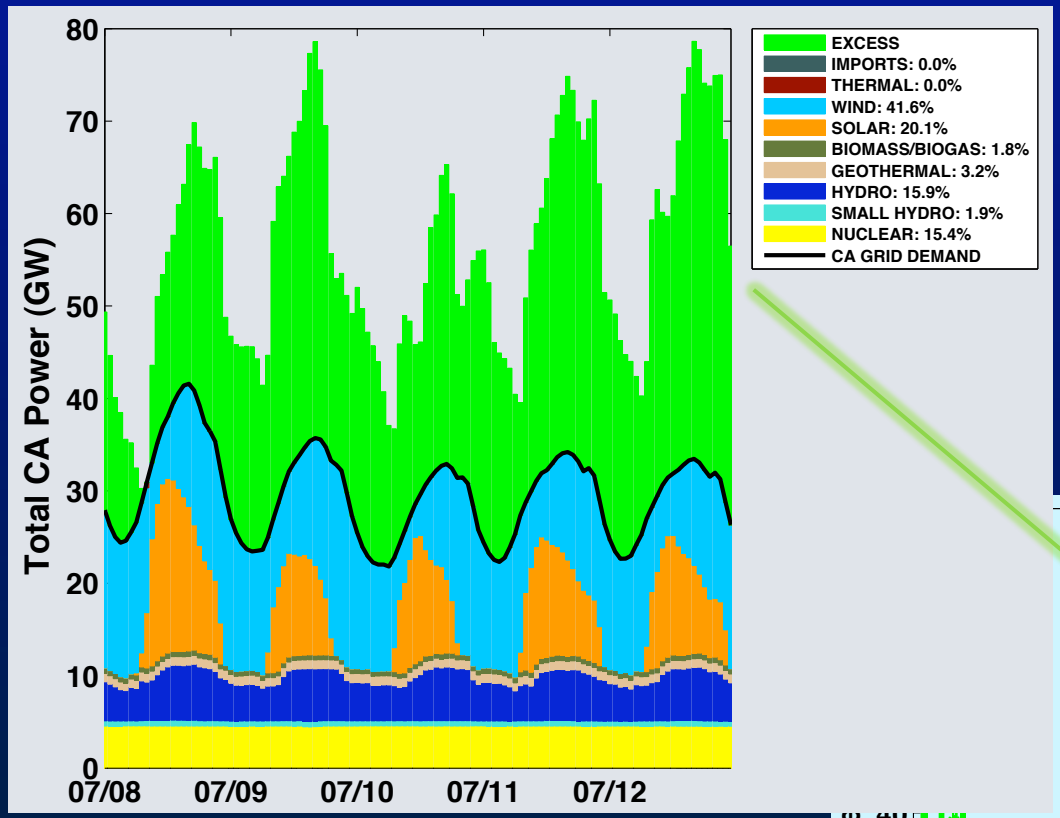


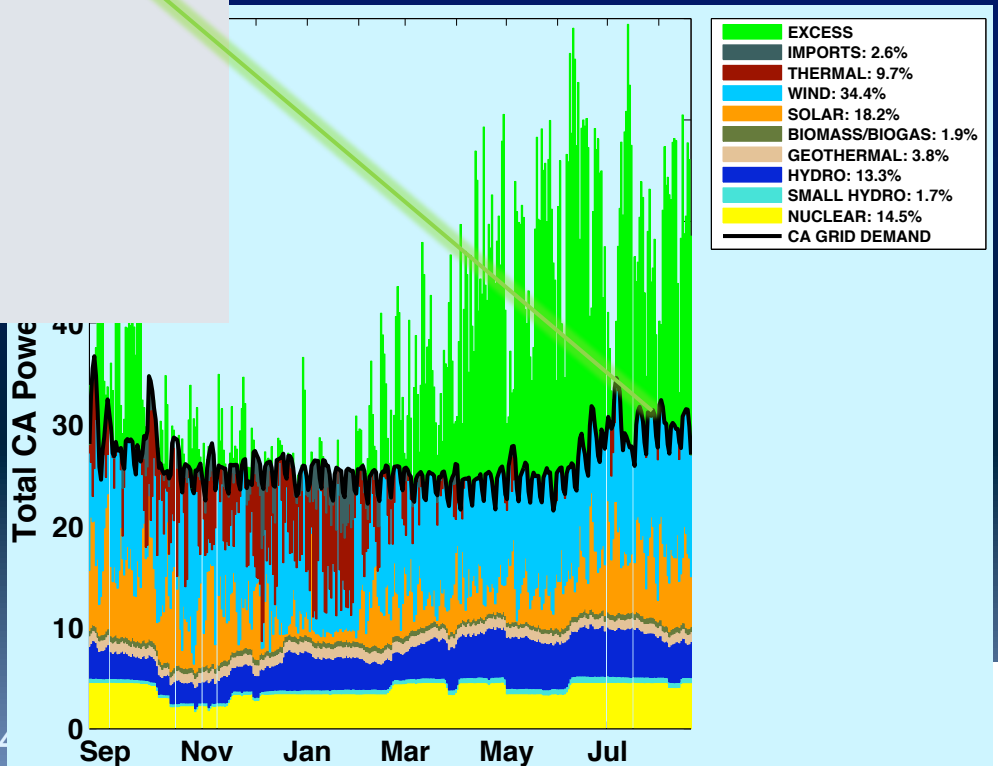
What would the CA be like @ 60% Renewables?

A Year in CA grid @ 60%

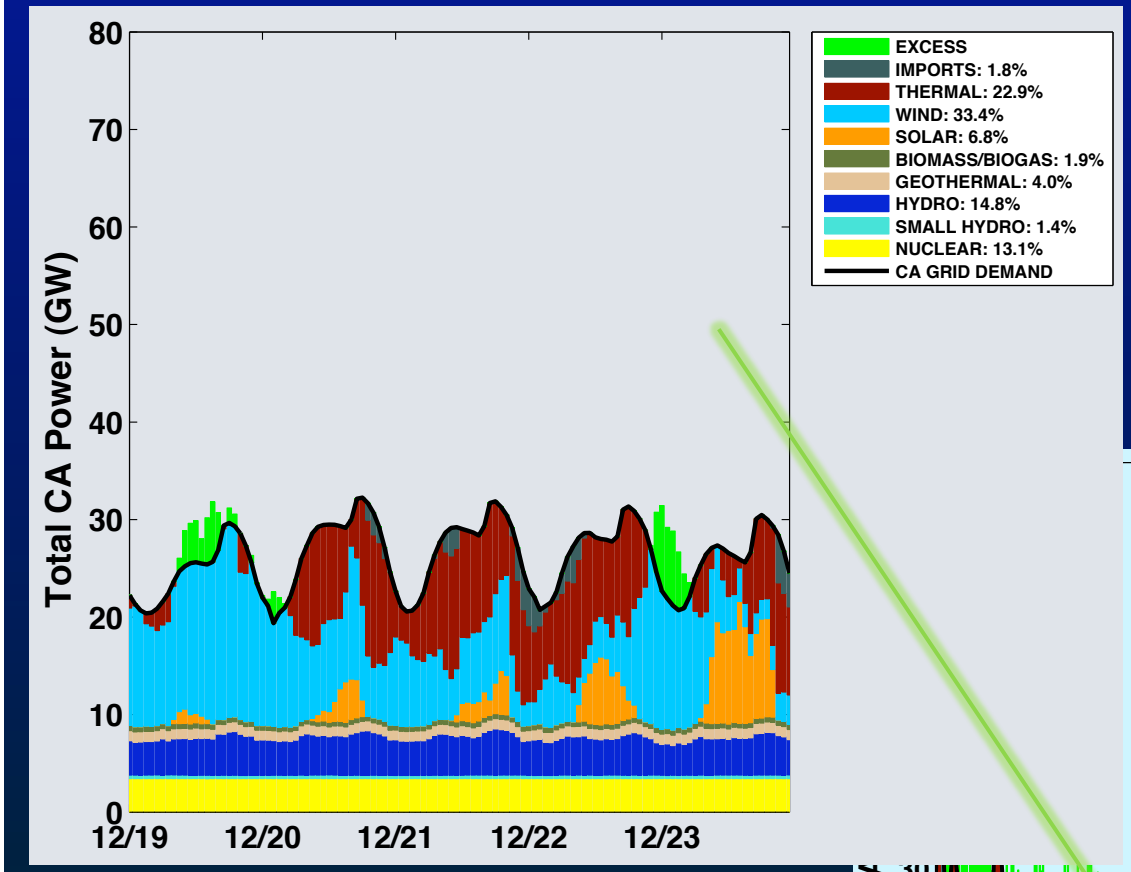


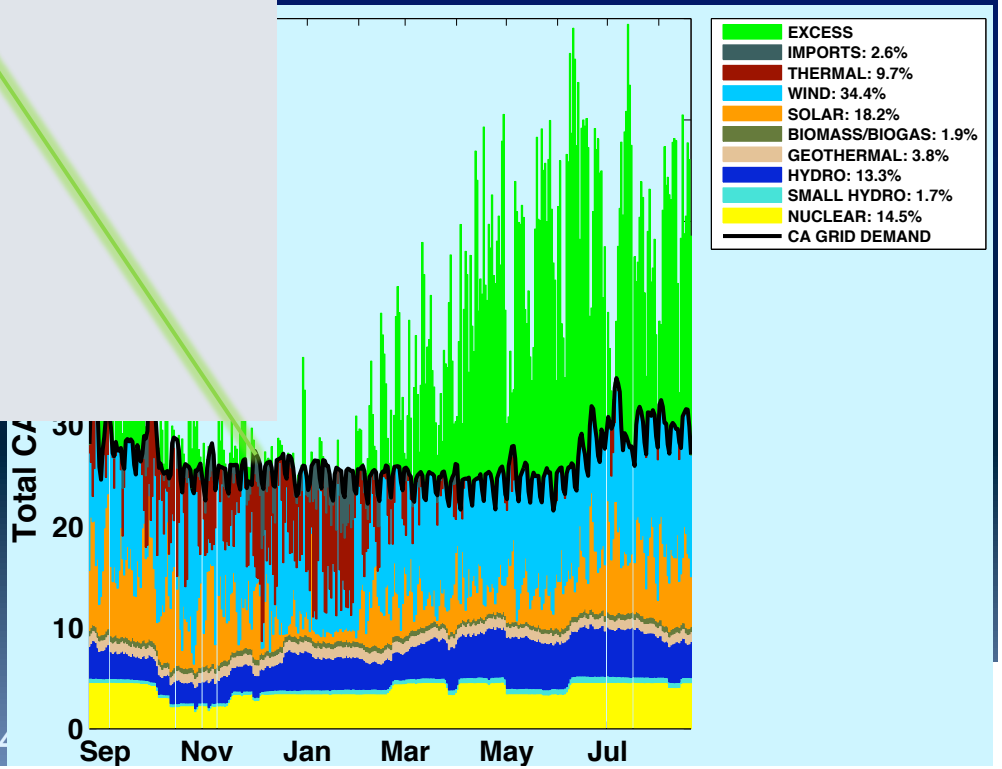
A Summer Week @ 60%





A Winter Week @ 60%





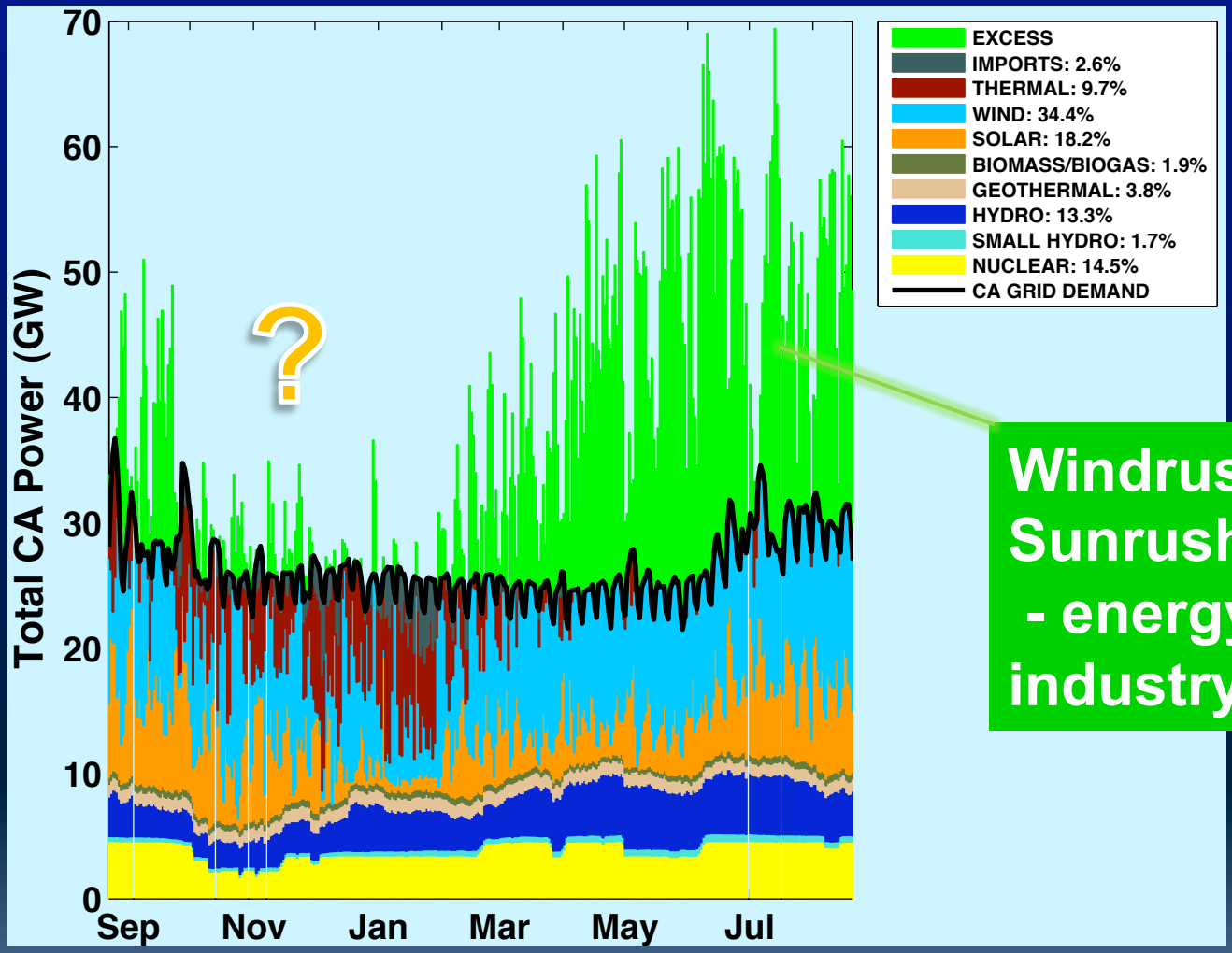
CA Grid @ 60%

	Current Grid			*Scaled Scenario - 60% Renewables*		
Generation Type	**Capacity / Peak (GW)**	**Total Energy (%)**	**Capacity Factor / Load Factor (%)**	**Capacity / Peak (GW)**	**Total Energy (%)**	**Capacity Factor / Load Factor (%)**
Renewables						
Geothermal	2.600 / 1.095	3.8%	38.7% / 92.0%	2.600 / 1.095	3.8%	38.7% / 92.0%
Biomass/Biogas	1.145 / 0.616	1.9%	43.5% / 80.9%	1.145 / 0.616	1.9%	43.5% / 80.9%
Small Hydro	1.380 / 0.646	1.7%	31.7% / 67.8%	1.380 / 0.646	1.7%	31.7% / 67.8%
Wind	2.812 / 2.470	3.1%	29.1% / 33.2%	57.116 / 22.995	34.4%	15.8% / 39.3%
Solar	0.403 / 0.457	0.4%	28.7% / 25.3%	29.792 / 30.636	18.2%	16.1% / 15.7%
Non-Renewables						
Nuclear	4.456 / 4.581	14.6%	86.0% / 83.6%	4.456 / 4.581	14.5%	86.0% / 83.6%
Hydro	12.574 / 6.286	13.3%	27.7% / 55.5%	12.574 / 6.286	13.3%	27.7% / 55.5%
Imports	N/A / 11.055	28.0%	N/A / 66.6%	N/A / 9.291	2.6%	N/A / 7.2%
Thermal	44.339 / 27.014	33.3%	19.7% / 32.4%	44.339 / 19.528	9.7%	5.7% / 13.0%
Total	**80.764 / 47.128**	**100.0%**	**32.6% / 55.8%**	**130.882 / 47.128**	**100.0%**	**20.1% / 55.8%**

What Can we do to Make it Work?

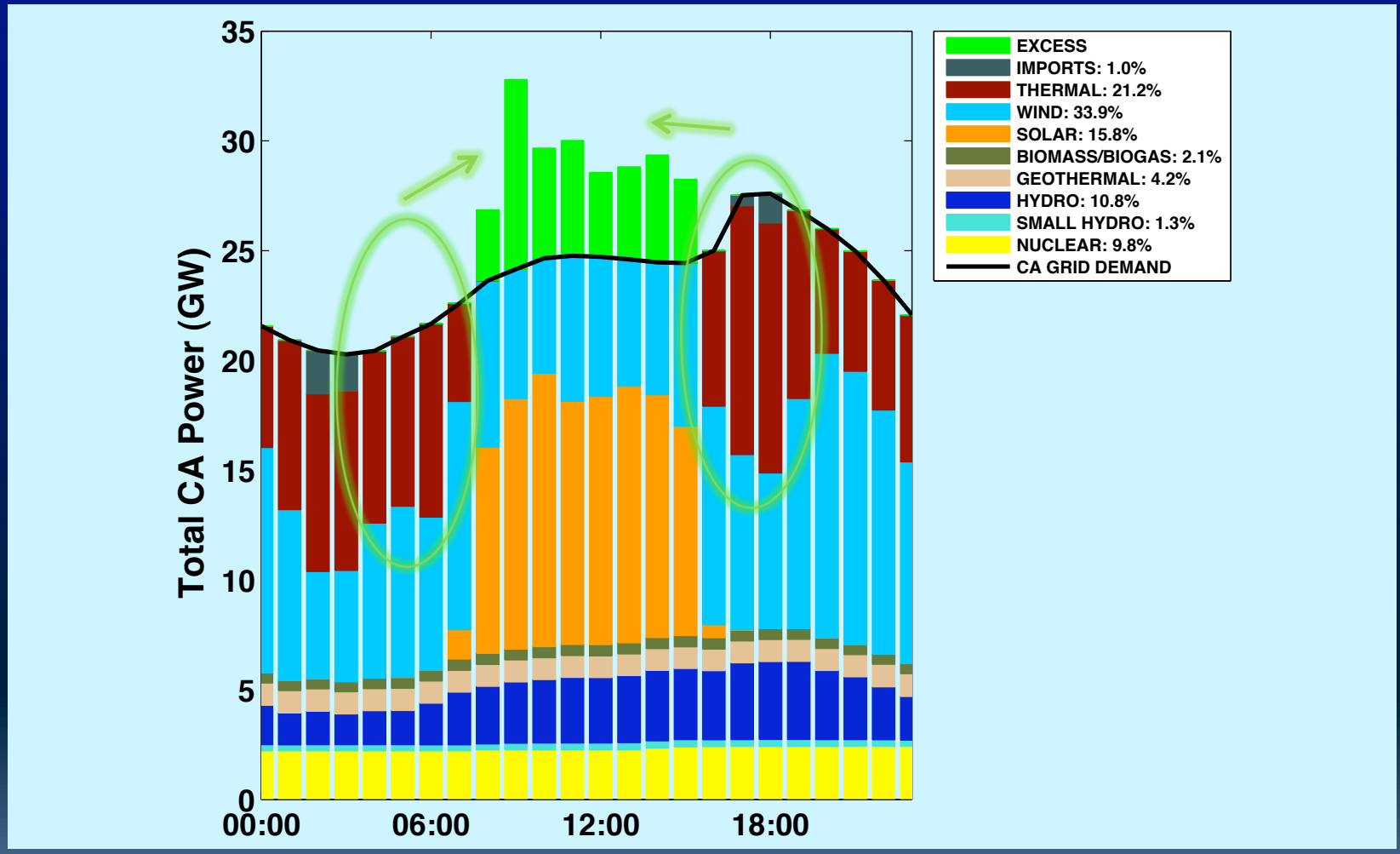
- Design for deep penetration
  - Optimize for the whole, not peak production…
  - Use your off-grid intuition
- Storage
  - Move energy in time
- Load scheduling (continuous DR)
  - Precooling, preheating, guardband adjustment
  - Deferral, acceleration
- Efficiency for shaping
  - Poor power proportionality of buildings and other loads, especially at night
- Integrated Portfolio Management
  - Utilize resources in concert with non-dispatcables
- Curtailment

Load shifting to follow supply



Windrush?
Sunrush?
- energy agile industry?

A Day

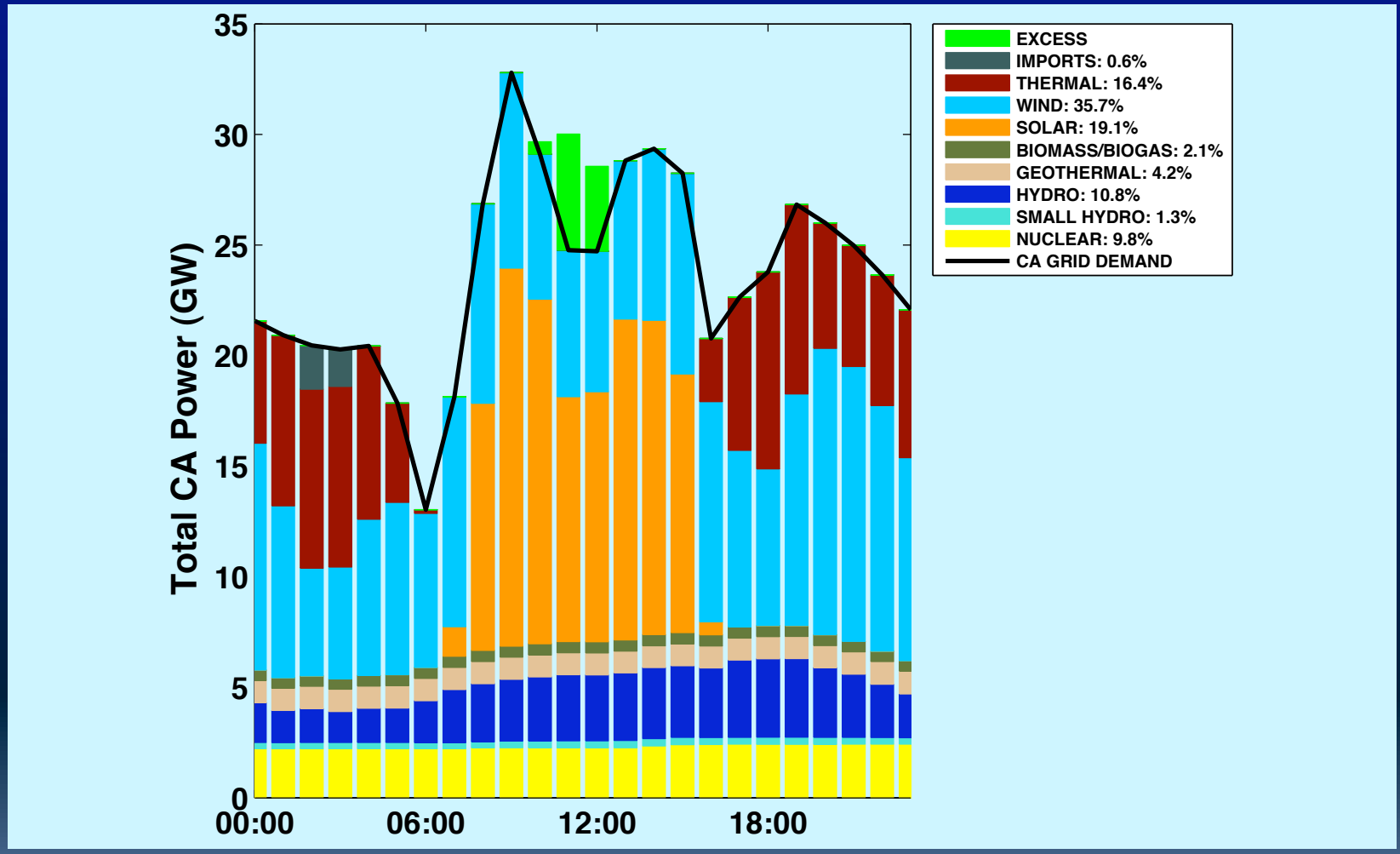

Total CA Power (GW)
35
30
25
20
15
10
5
0
00:00
06:00
12:00
18:00
EXCESS
IMPORTS: 1.0%
THERMAL: 21.2%
WIND: 33.9%
SOLAR: 15.8%
BIOMASS/BIOGAS: 2.1%
GEOTHERMAL: 4.2%
HYDRO: 10.8%
SMALL HYDRO: 1.3%
NUCLEAR: 9.8%
CA GRID DEMAND

Simple Optimistic Shift

- find the best possible strategy for shifting fossil fuel demand to excess renewable generation

- Process:
  - Construct a list of possible shifting opportunities
    - FF use within k hours of excess
  - Move the load that must shift the furthest from fossil to renewables
  - Iterate until no more shifting is possible

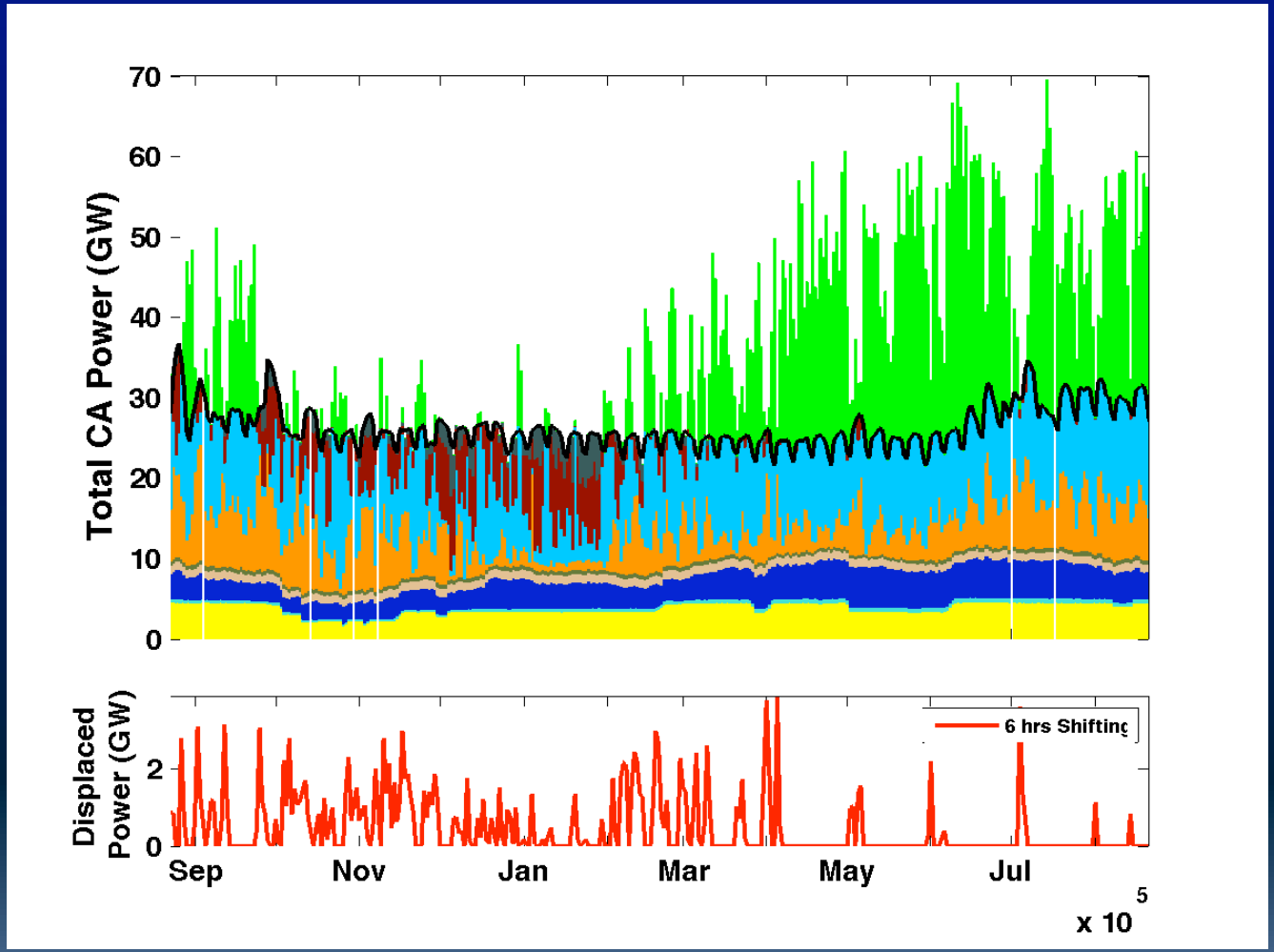
The Day with +/- 3 hours of shift



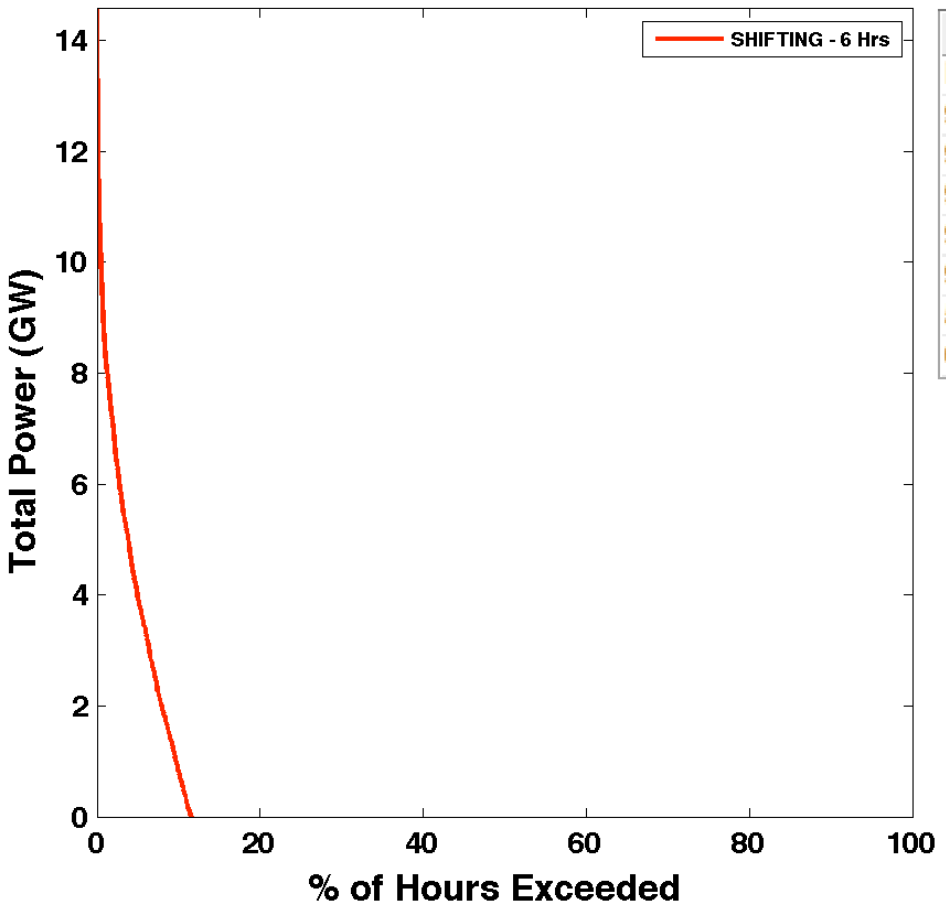
Load shifting Algorithm

- Optimistic ?
  - Any amount of load at any time
- Conservative ?
  - Simplistic local algorithm

How much does Shifting help?

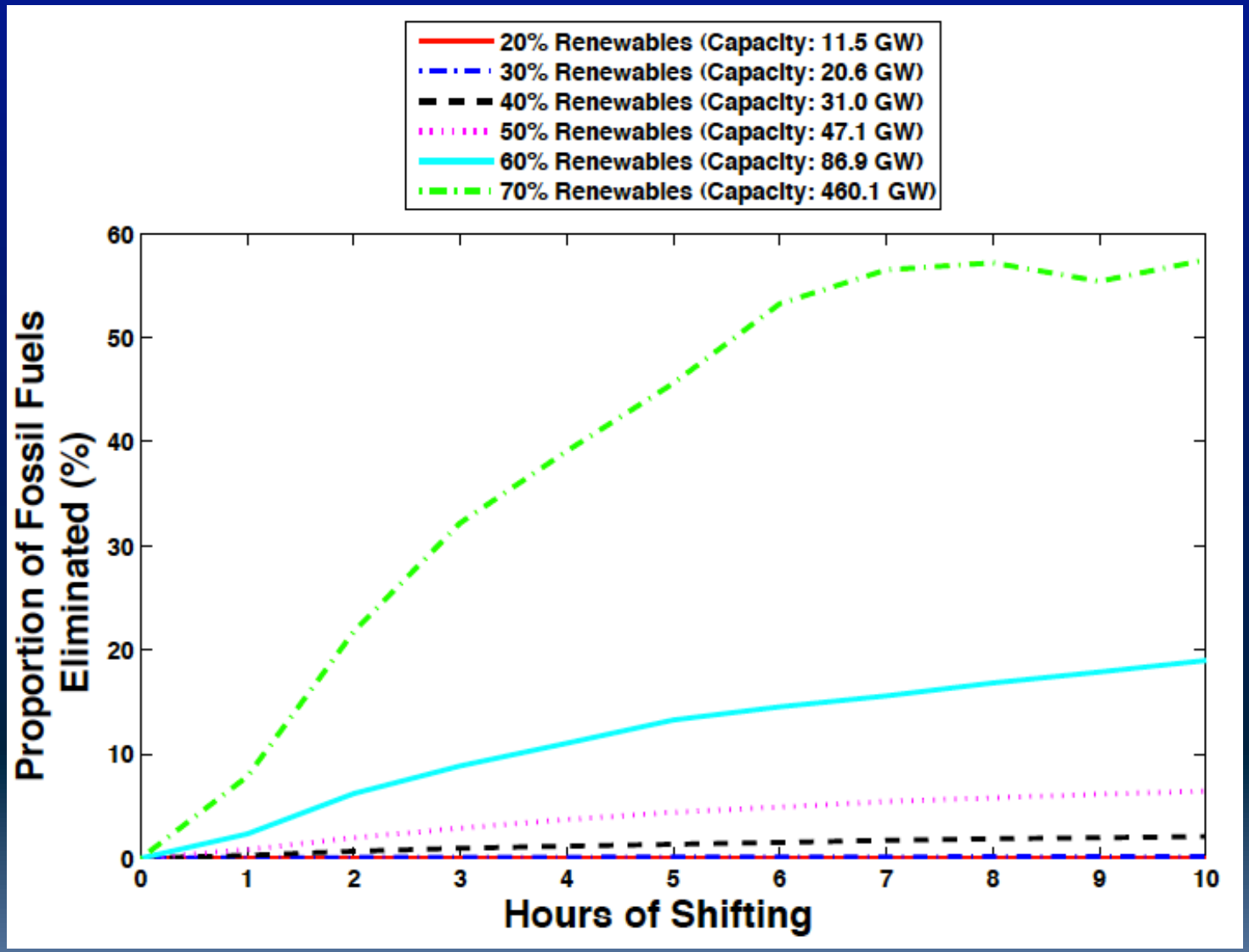


Shifting



%Hrs	GW
Max	14.574
99.9	12.944
99.5	10.168
99.0	8.394
95.0	3.981
90.0	0.846
50.0	0.000
0.0	0.000

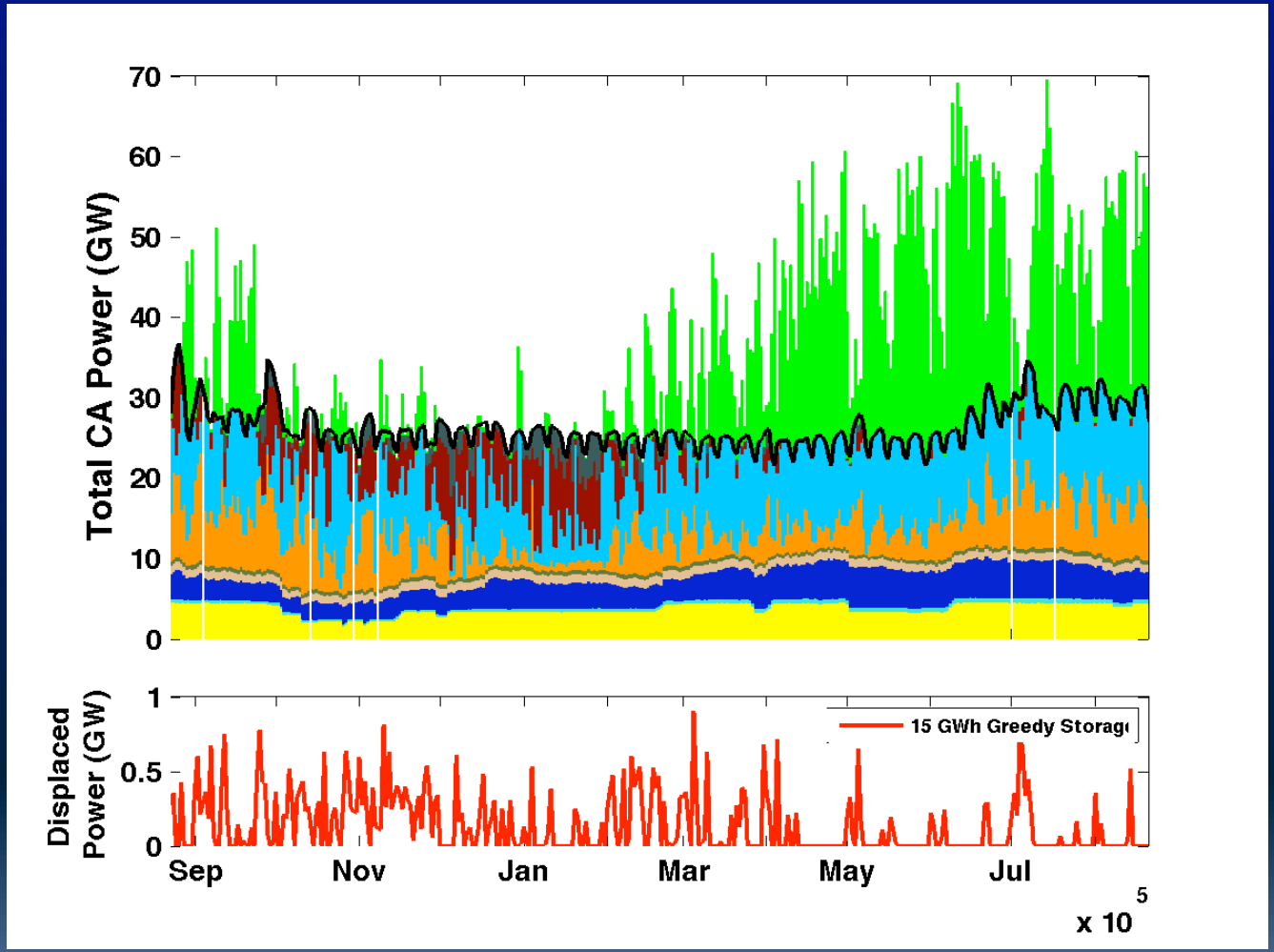
Effects of Demand Shifting



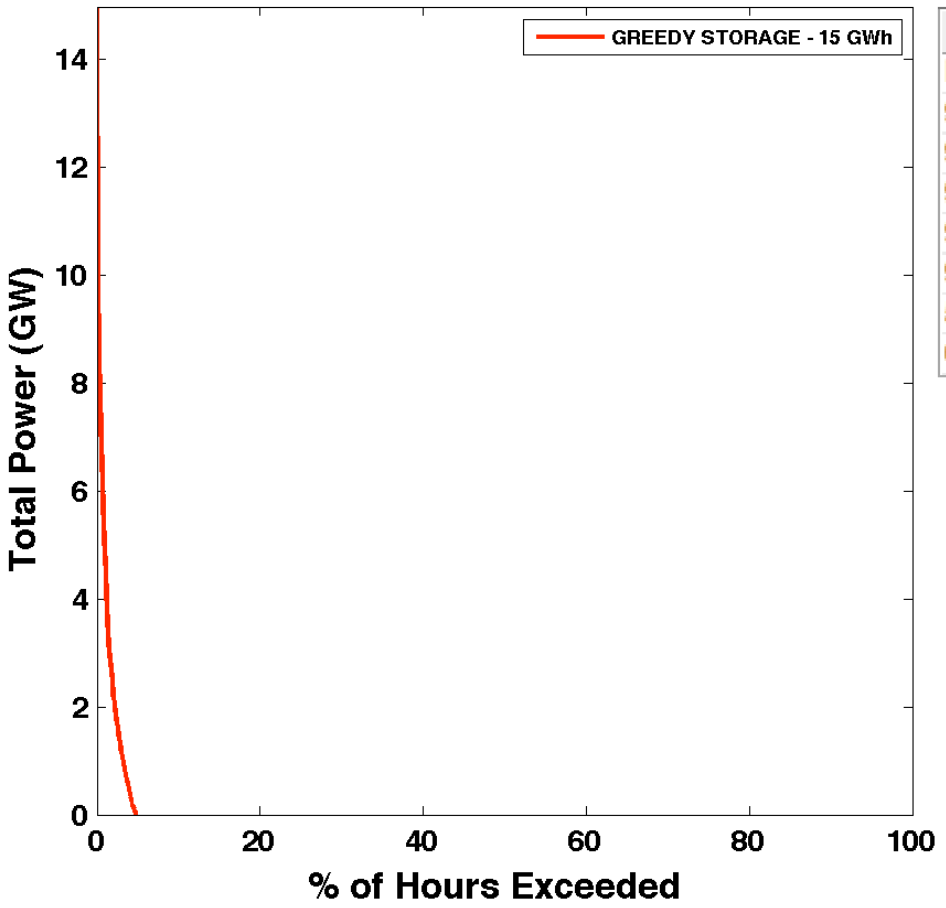
Storage Algorithm

- **Fill** whenever there is excess generations and storage capacity.
- Dispatch whenever storage is greater than zero and import or thermal energy is being used.
  - Imports are first displaced, and then thermal is displaced.
  - No restrictions on maximum dispatchable power, i.e. all storage can be dispatched in a single timestep (1 hour).

Storage (15 GWh)



Storage

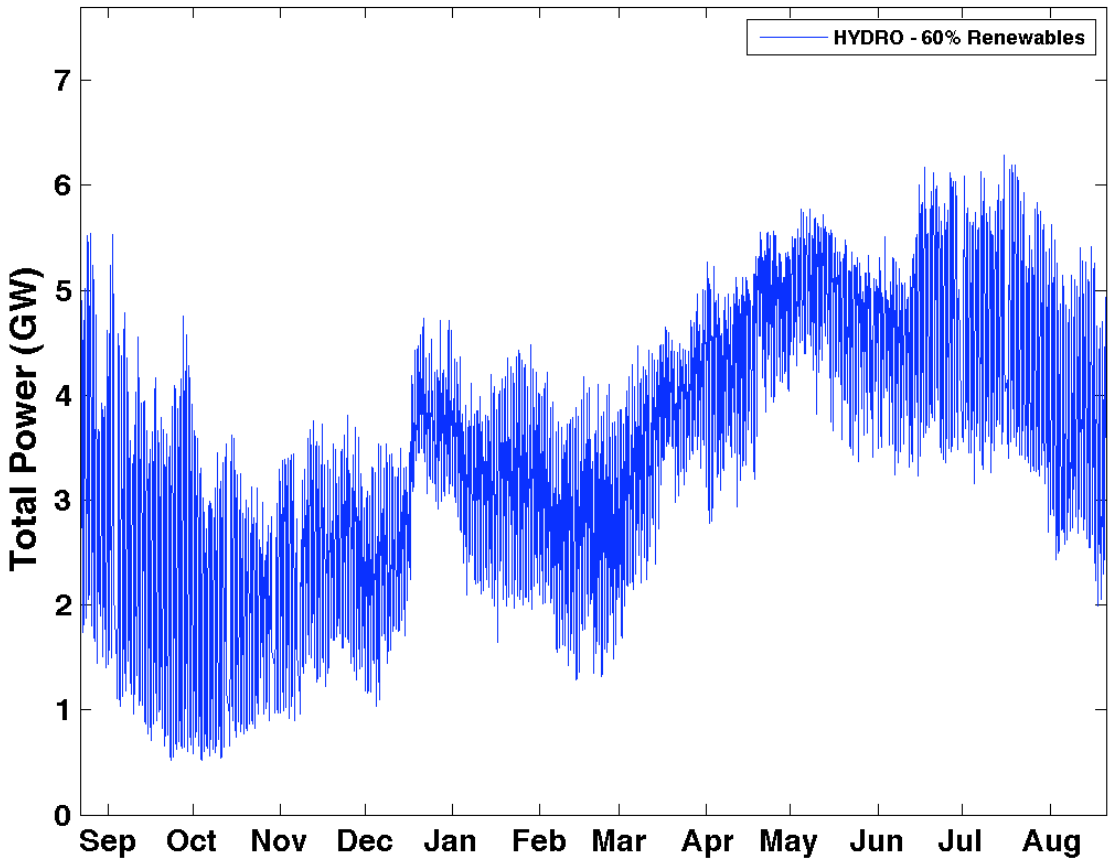


%Hrs	GW
Max	14.972
99.9	10.579
99.5	7.348
99.0	4.927
95.0	0.000
90.0	0.000
50.0	0.000
0.0	0.000

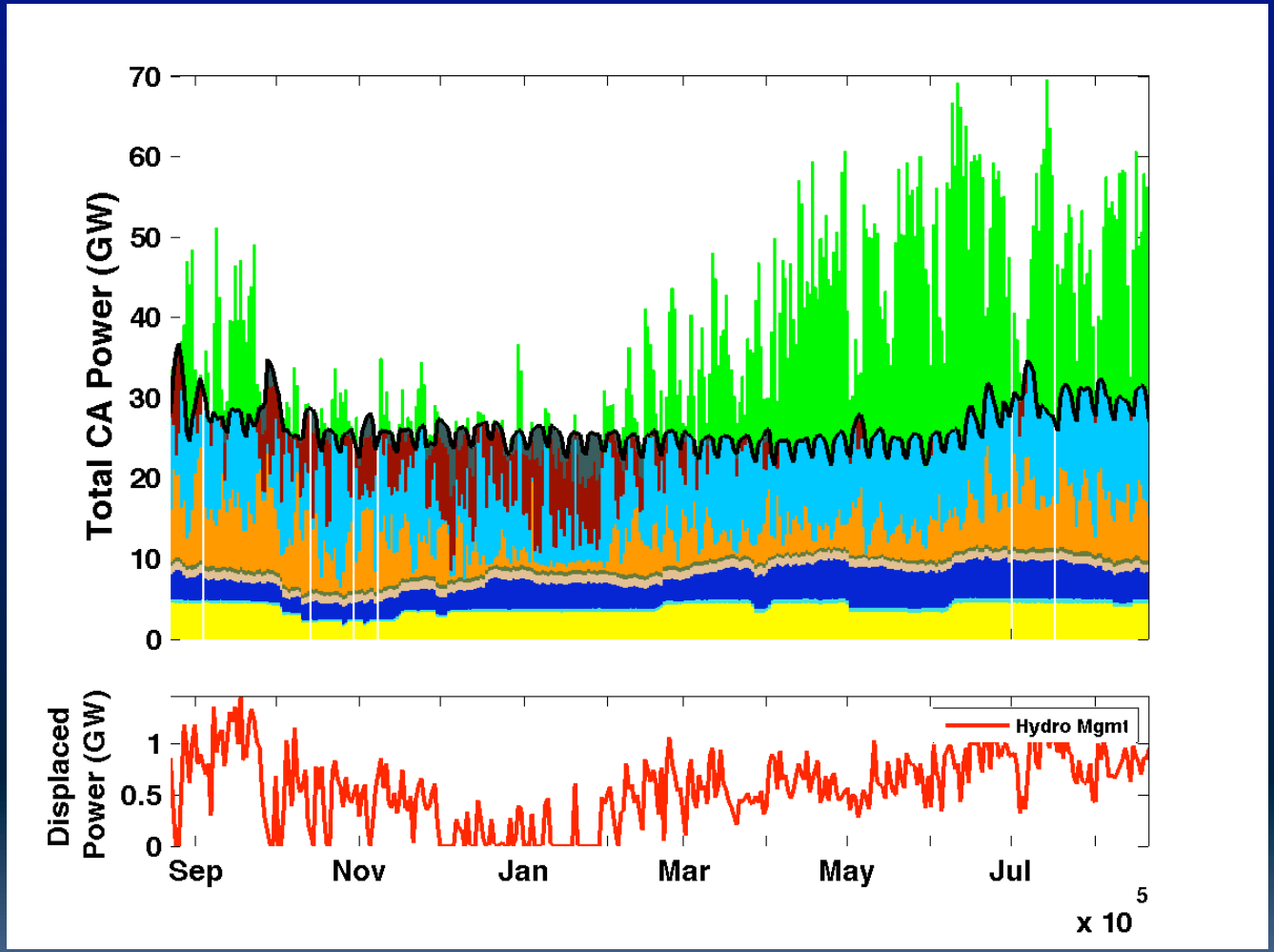
Hydro for firming

- Daily dispatchable energy is calculated as the integral over all hours in a day of hydro power minus the daily minimum.
- Then the dispatchable energy is distributed to minimize the peak import power of the day, with any excess being used to minimize the peak thermal power of the day.

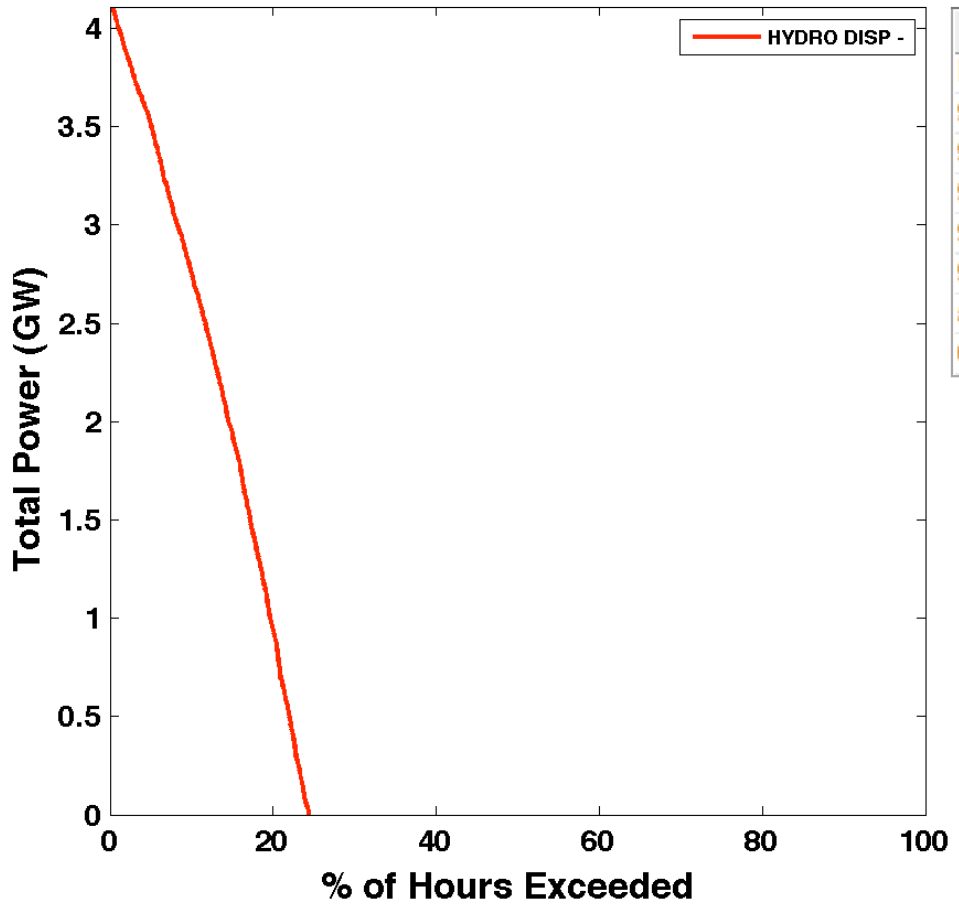
Large Hydro


HYDRO - 60% Renewables
Total Power (GW)
0
1
2
3
4
5
6
7
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug

How much does Hydro help?



Hydro scheduling



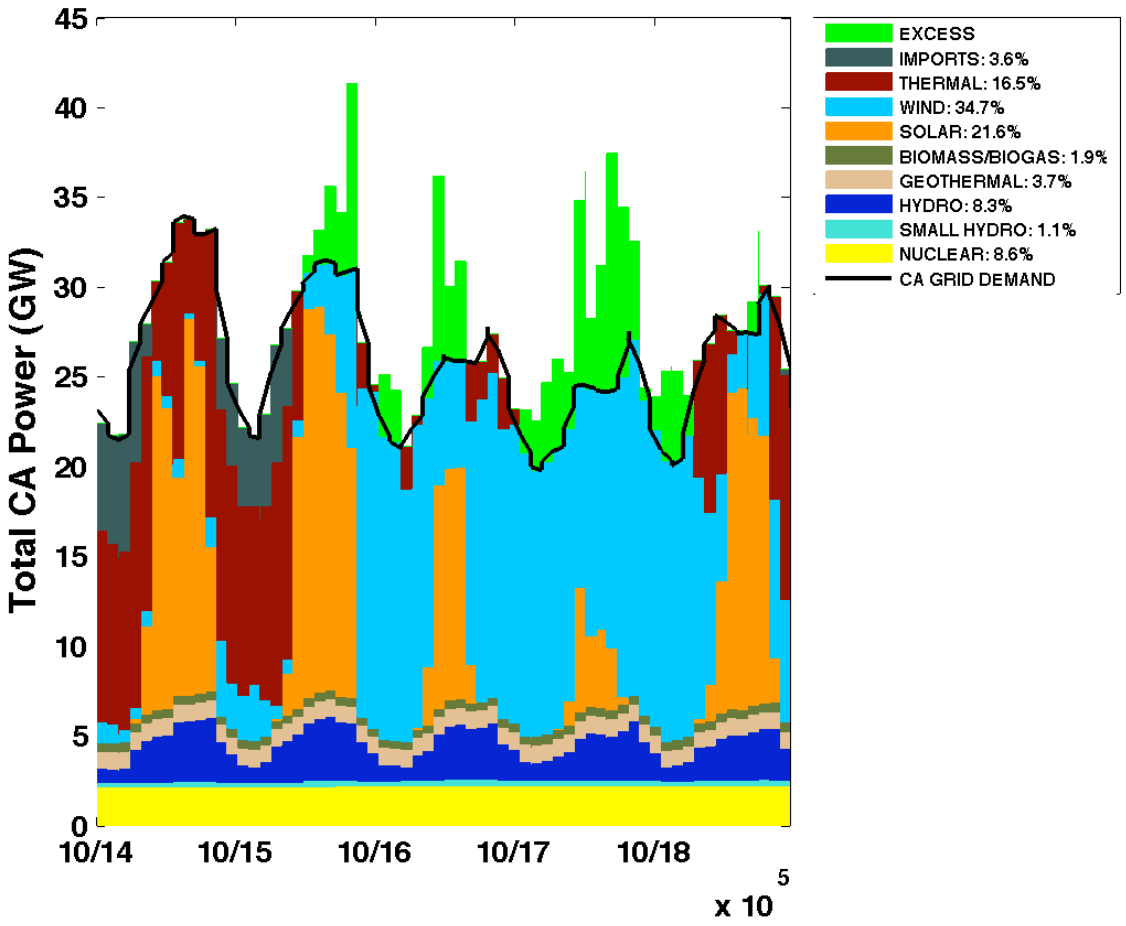
%Hrs	GW
Max	4.111
99.9	4.111
99.5	4.097
99.0	4.017
95.0	3.517
90.0	2.768
50.0	0.000
0.0	0.000

Techniques

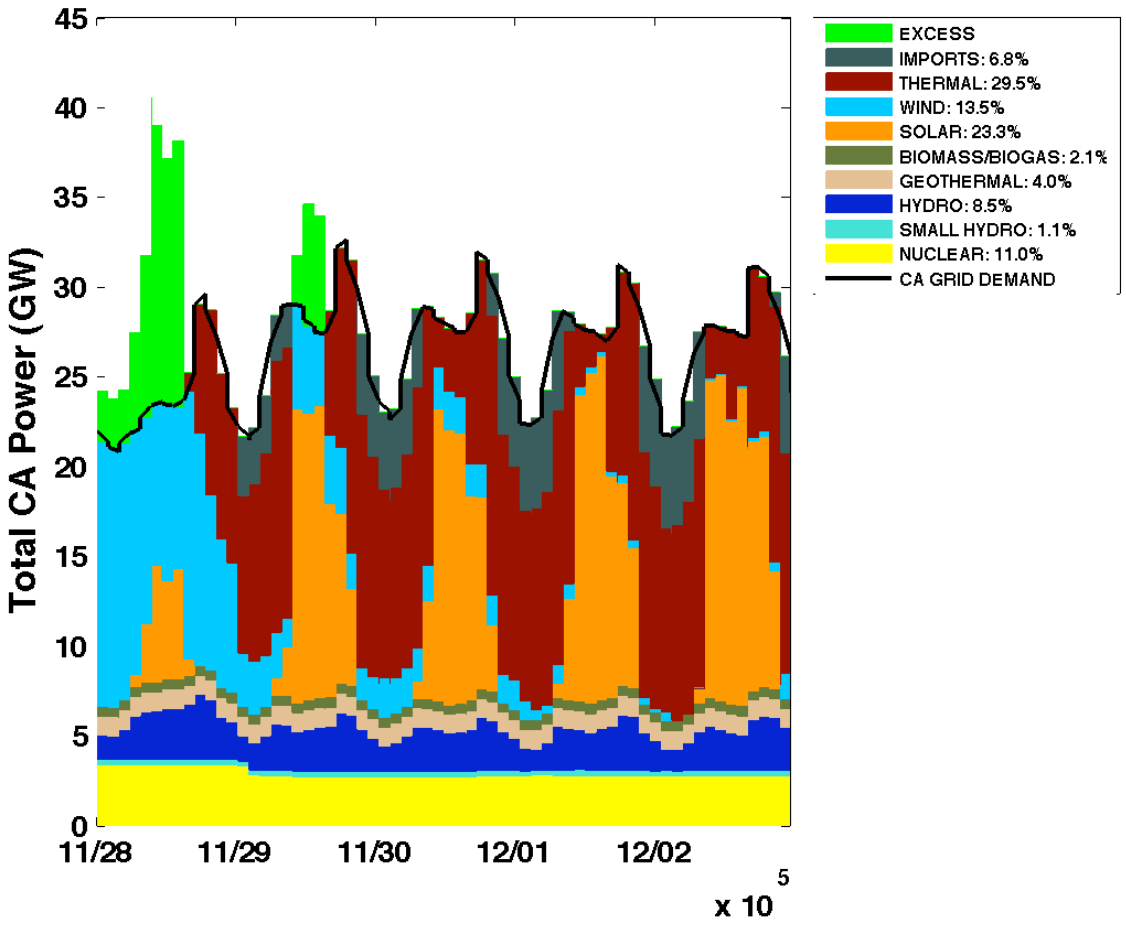
- Idealistic utilization of the resources
- Simple mechanisms
  - Charge using fossil ?
  - Delay Discharge ?
- Ought to consider all in cooperation

- Are these enough?

A tough week


45
40
35
30
25
20
15
10
5
0
Total CA Power (GW)
10/14
10/15
10/16
10/17
10/18
x 10^5
EXCESS
IMPORTS: 3.6%
THERMAL: 16.5%
WIND: 34.7%
SOLAR: 21.6%
BIOMASS/BIOGAS: 1.9%
GEOTHERMAL: 3.7%
HYDRO: 8.3%
SMALL HYDRO: 1.1%
NUCLEAR: 8.6%
CA GRID DEMAND

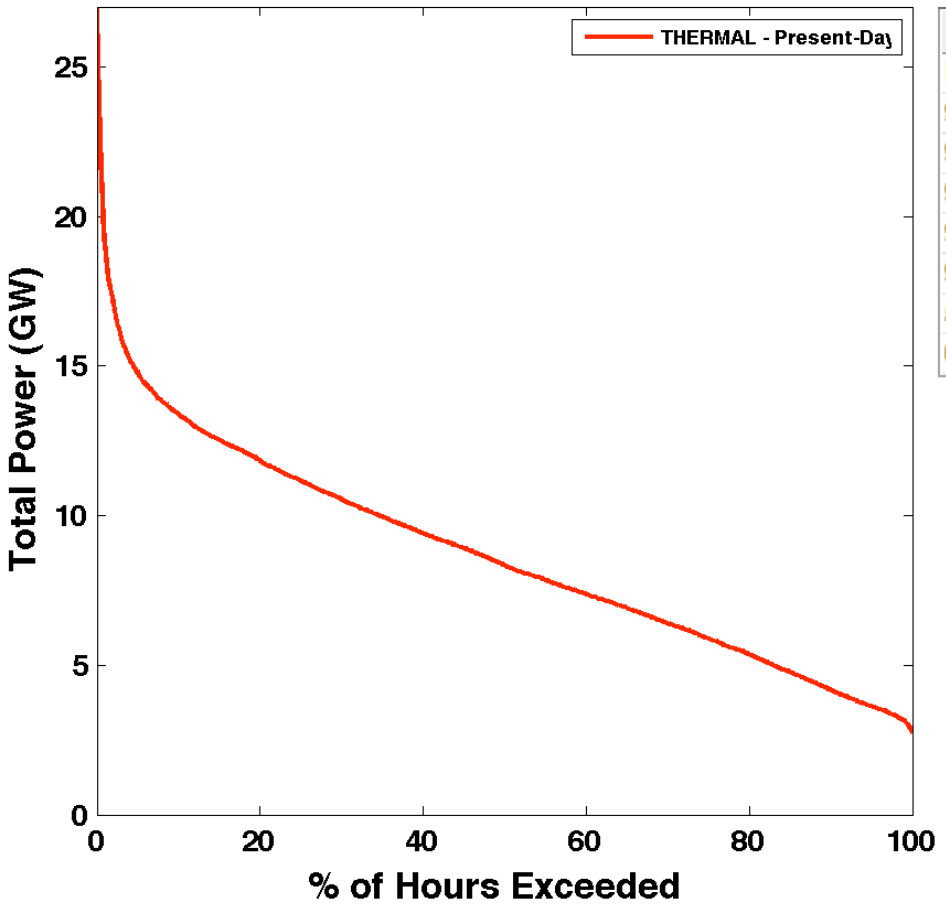
Another


45
40
35
30
25
20
15
10
5
0
Total CA Power (GW)
11/28
11/29
11/30
12/01
12/02
x 10^5
EXCESS
IMPORTS: 6.8%
THERMAL: 29.5%
WIND: 13.5%
SOLAR: 23.3%
BIOMASS/BIOGAS: 2.1%
GEOTHERMAL: 4.0%
HYDRO: 8.5%
SMALL HYDRO: 1.1%
NUCLEAR: 11.0%
CA GRID DEMAND

The winter night time lulls?

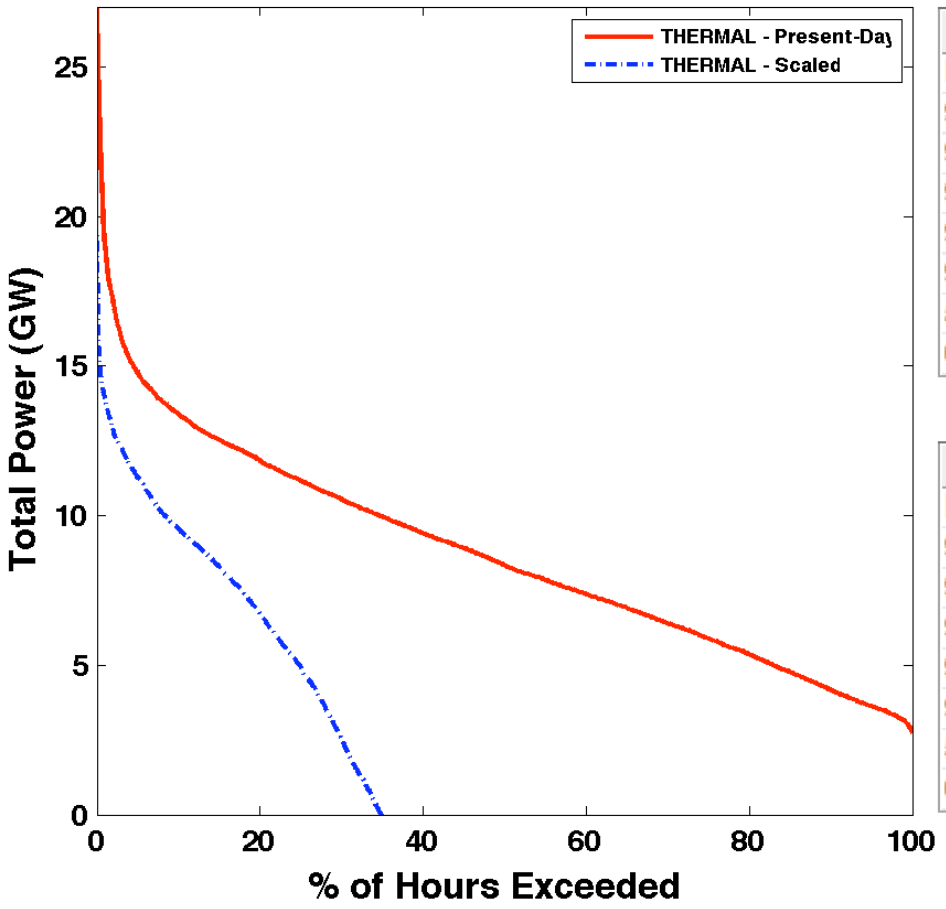
- Efficiency !!!
  - Lighting
  - Nighttime setbacks
- Curtailment
- Long term storage
- It' called "fuel"

What does this mean for thermal?



%Hrs	GW
Max	27.014
99.9	25.779
99.5	21.887
99.0	19.144
95.0	14.812
90.0	13.414
50.0	8.368
0.0	2.720

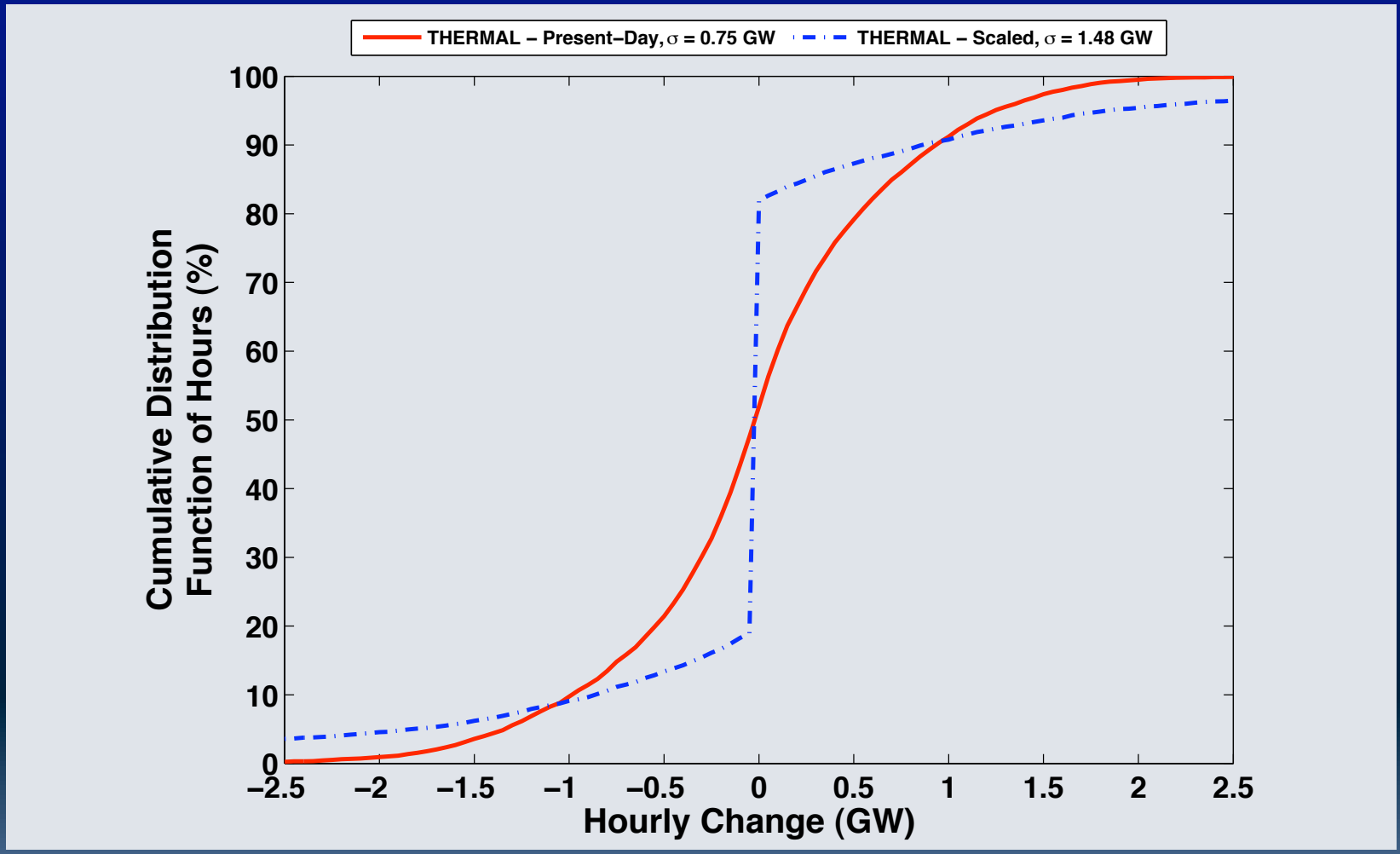
Thermal @ 60%



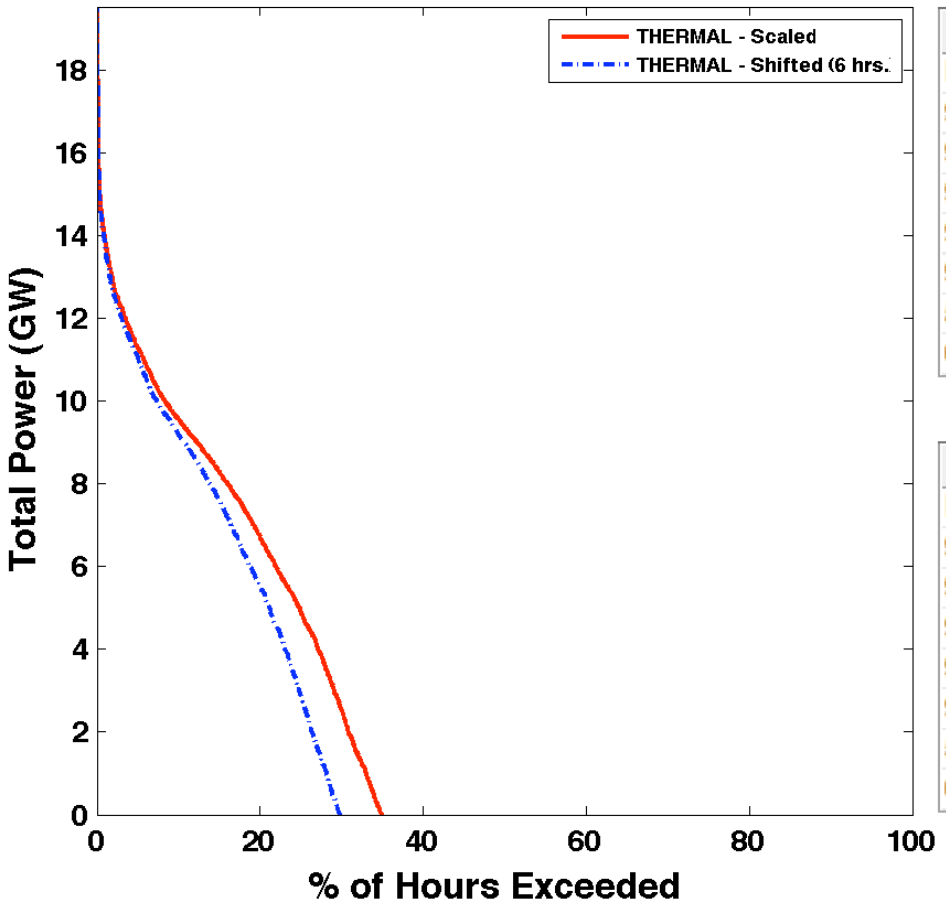
%Hrs	GW
Max	27.014
99.9	25.779
99.5	21.887
99.0	19.144
95.0	14.812
90.0	13.414
50.0	8.368
0.0	2.720

%Hrs	GW
Max	19.528
99.9	16.693
99.5	14.569
99.0	13.905
95.0	11.314
90.0	9.588
50.0	0.000
0.0	0.000

Ramps


THERMAL – Present–Day, σ = 0.75 GW
THERMAL – Scaled, σ = 1.48 GW
Cumulative Distribution Function of Hours (%)
100
90
80
70
60
50
40
30
20
10
0
–2.5
–2
–1.5
–1
–0.5
0
0.5
1
1.5
2
2.5
Hourly Change (GW)

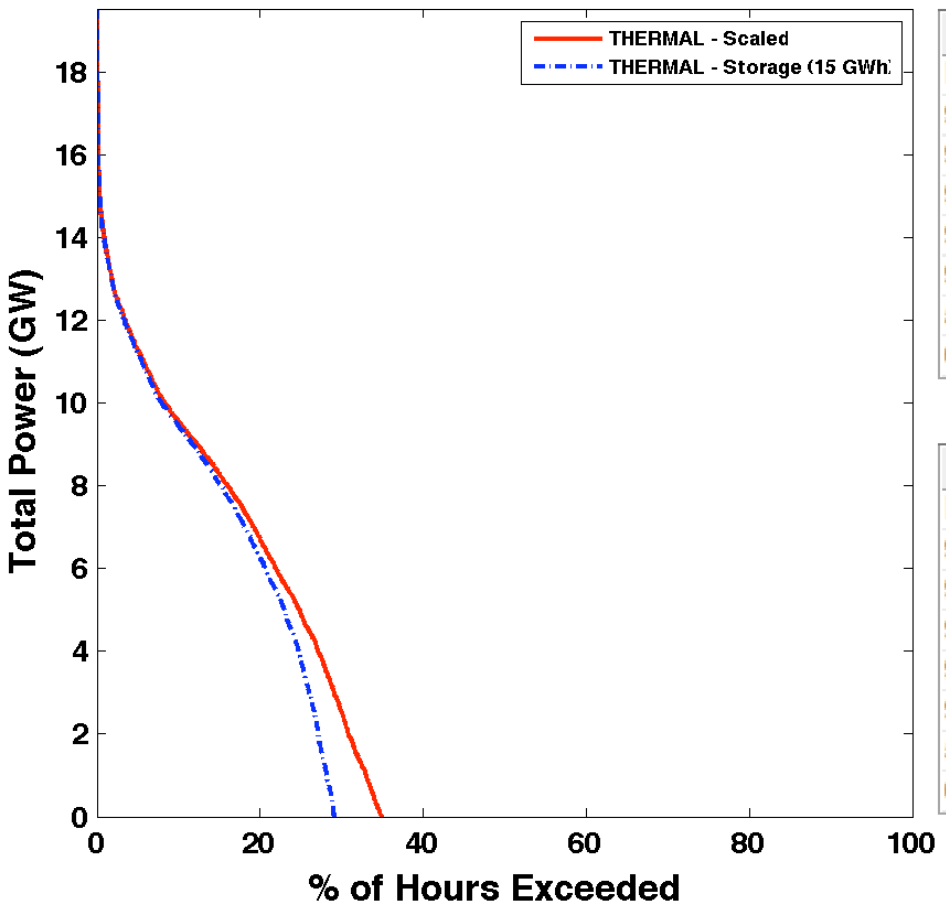
Thermal with Shifting



%Hrs	GW
Max	19.528
99.9	16.693
99.5	14.569
99.0	13.905
95.0	11.314
90.0	9.588
50.0	0.000
0.0	0.000

%Hrs	GW
Max	19.528
99.9	16.693
99.5	14.530
99.0	13.794
95.0	11.092
90.0	9.207
50.0	0.000
0.0	0.000

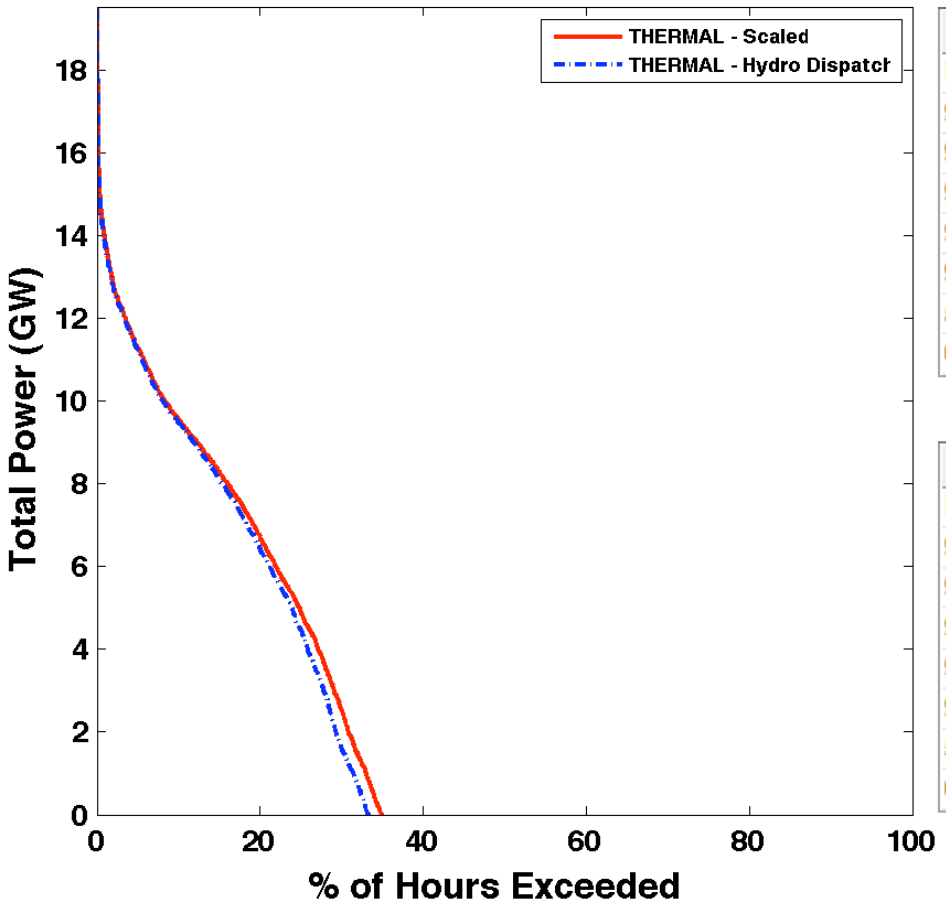
Thermal with Storage



%Hrs	GW
Max	19.528
99.9	16.693
99.5	14.569
99.0	13.905
95.0	11.314
90.0	9.588
50.0	0.000
0.0	0.000

%Hrs	GW
Max	19.528
99.9	16.693
99.5	14.558
99.0	13.885
95.0	11.258
90.0	9.462
50.0	0.000
0.0	0.000

Thermal with Hydro scheduling



%Hrs	GW
Max	19.528
99.9	16.693
99.5	14.569
99.0	13.905
95.0	11.314
90.0	9.588
50.0	0.000
0.0	0.000

%Hrs	GW
Max	19.528
99.9	16.693
99.5	14.547
99.0	13.885
95.0	11.261
90.0	9.503
50.0	0.000
0.0	0.000

Opportunities

- Here greedy techniques to minimize thermal and import energy
- Results in very expensive production
- Optimize storage, shifting, and hydro in concert with thermal production

- And then iterate to capture network constraints

Conclusion

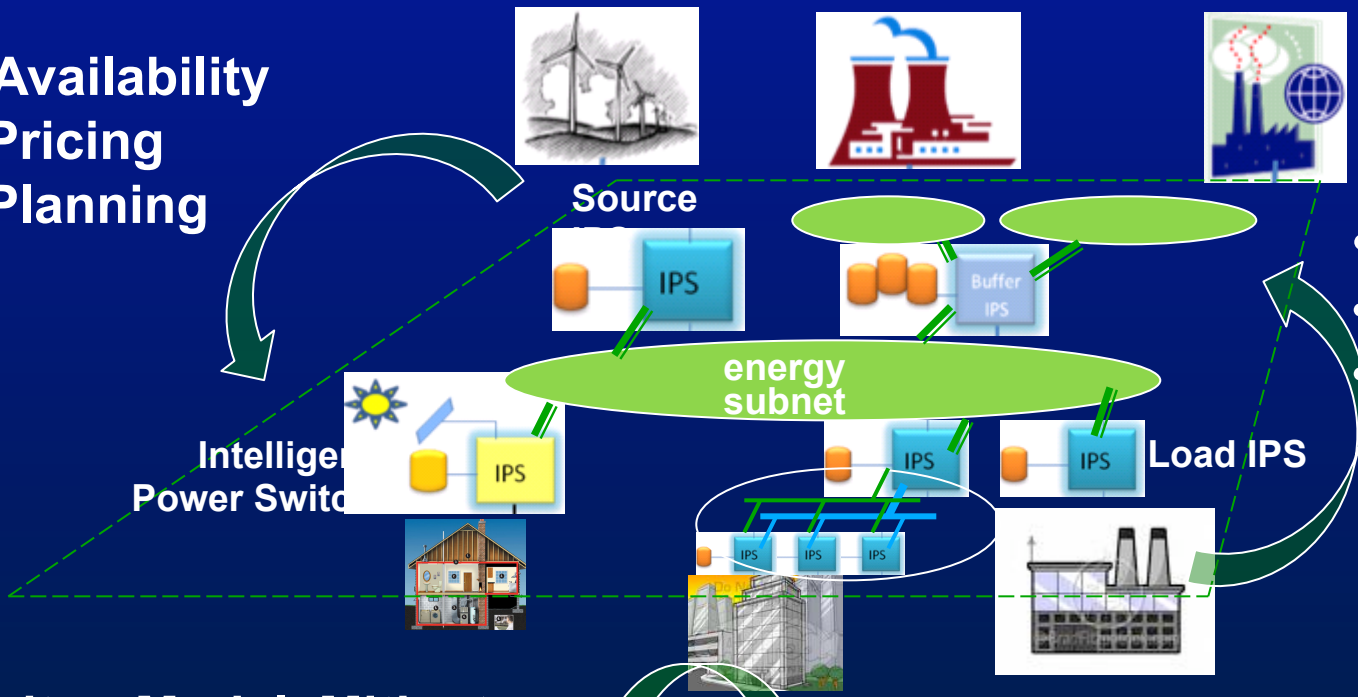
- The key challenges posed by a 60% grid are very different from those we are concentrating on today
  - Peak summer cooling => winter night lulls
- Supply and Demand management are far more important with deep penetration
  - Fundamentally limited by seasonal dynamics
  - Need to apply them all in concert
- Whole-grid integrated asset management
  - Its about dynamics, not just statistics
- Peak shaving and ramp mgmt return in a new and critical form
- New energy-agile industries ?

To Read more

- Defining CPS Challenges in a Sustainable Electricity Grid, Jay Taneja, Randy Katz, and David Culler, ICCPS, April 2012
- E. K. Hart, E. D. Stoutenburg, and M. Z. Jacobson, "The Potential of Intermittent Renewables to Meet Electric Power Demand: Current Methods and Emerging Analytical Techniques," Proc. IEEE, 100(2): 322-334, 2012. doi:10.1109/JPROC.2011.2144951.
- The Future of the Electric Grid, Interdisciplinary MIT Study

Think Cooperative Grid

- Availability
- Pricing
- Planning



- Forecasting
- Tracking
- Market

Monitor, Model, Mitigate

- Deep instrumentation
- Waste elimination
- Efficient Operation

Shifting, Scheduling, Adaptation